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GEOLOGY

PETROLOGY

Intrusive ultrabasic rocks and their metamorphic relationships at Leech Lake Mountain, Mendocino Co., California, by Charles W. Chesterman. Page 5

ENGINEERING GEOLOGY

Geology of the sedimentary deposits in San Francisco Bay, California, by Ray C. Treasher. Page 11

Engineering properties and problems of the San Francisco Bay mud, by James K. Mitchell. Page 25

PHOTOGEOLOGY

Fracture traces in the Tuscan Formation, northern California, by John L. Burnett. Page 33

PALEONTOLOGY

Fossil evidence for maximum age of metamorphism in part of the Franciscan Formation, northern Coast Ranges, California, by Edward D. Ghent. Page 41

SHORT CONTRIBUTIONS

to California Geology

SPECIAL REPORT 82

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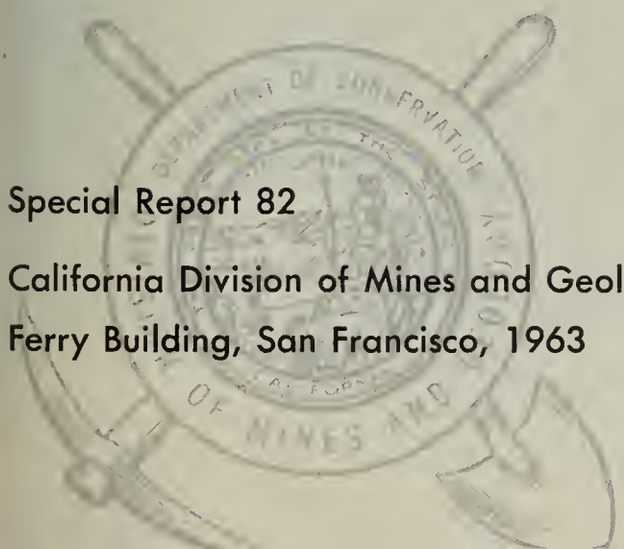

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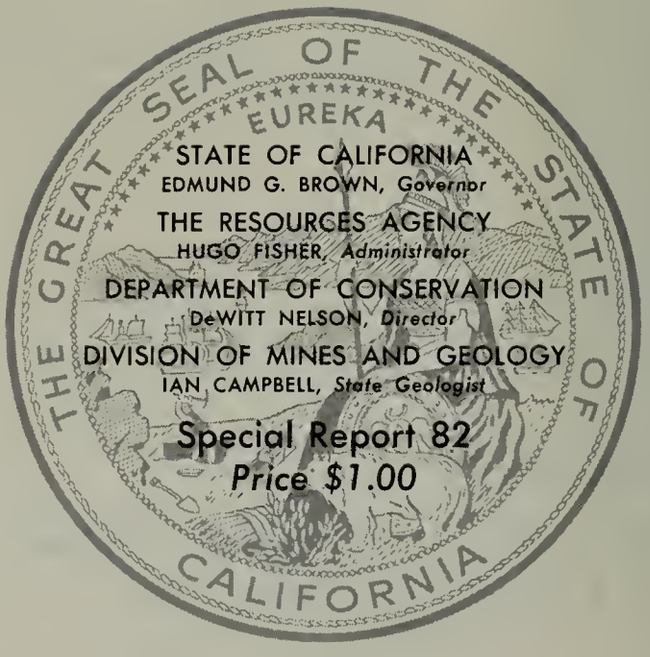

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PREFACE

With this issue, the Division of Mines and Geology is initiating a new mode of publication within the long established Special Report series—Short Contributions to California Geology. The short contribution is a useful format because it allows the writer to present his most significant results concisely without the general descriptive information that is required in a more formalized report.

From a publishing standpoint, several brief reports can be published more economically under one cover than in individual volumes simply due to the mechanics of printing and binding. When more short contributions are available for publication, we hope to combine them into similar volumes.

JOHN L. BURNETT

Geologist, Division of Mines and Geology
San Francisco, May 1963

INTRUSIVE ULTRABASIC ROCKS AND THEIR METAMORPHIC RELATIONSHIPS AT LEECH LAKE MOUNTAIN, MENDOCINO COUNTY, CALIFORNIA*

By CHARLES W. CHESTERMAN

Geologist, California Division of Mines and Geology, San Francisco

ABSTRACT

Intrusive contacts between sills of serpentinite and tuffaceous graywackes of the Franciscan Formation are excellently exposed at Leech Lake Mountain. Exposures of such contacts are exceedingly rare in California. This one was studied in detail, in the field and in the laboratory.

The ultrabasic rock was emplaced as a liquid peridotitic magma, not as serpentinite. A metamorphic effect of the intrusion was the formation of much jadeitic pyroxene and smaller amounts of blue sodic amphibole in the graywacke. This mineral assemblage indicates a grade of metamorphism in the glaucophane schist facies, although glaucophane itself is scarce. The intrusion was accompanied by a hydrothermal phase which 1) partly serpentinized the graywacke immediately at the contact; 2) formed veins of nephrite, jadeitic pyroxene, hydrogrossular, and vesuvianite in the serpentinite, and 3) formed monomineralic veinlets of pectolite, xonotlite, and calcite in the graywacke.

Diabase sills were intruded between beds of chert before the ultrabasic sills were emplaced. Locally the diabase was intruded by the later peridotite; at these contacts the peridotite was altered to nephrite, and the diabase was altered to a chlorite - serpentine - kaersutite - actinolite - pumpellyite rock. The hydrothermal phase that accompanied the intrusion of the peridotite affected all of the diabase: the feldspar was altered in part to pumpellyite; the titaniferous augite was altered to chlorite, pale-green actinolite, and blue amphibole (crossite); and the ilmenite and sphene were altered to leucoxene.

* Revised from the Report of the International Geological Congress, XXI Session, Norden, 1960, (Part XIII, Petrographic Provinces, Igneous and Metamorphic Rocks) Copenhagen, Denmark, pages 208-215.

INTRODUCTION

Leech Lake Mountain is in the central part of the northern Coast Ranges of California in northern Mendocino County, about 175 miles north of San Francisco. The area is accessible by trail from the Eel River Ranger Station which is 11 miles south of Leech Lake Mountain and 13 miles east of Covelo.

An area of approximately five square miles around Leech Lake Mountain was mapped on a scale of 1000 feet to the inch on an enlarged portion of the U.S. Geological Survey Covelo quadrangle (1953 edition).

To Dr. J. R. McNitt of the California Division of Mines and Geology and Dr. F. J. Turner, Professor of Geology at the University of California, Berkeley, I am indebted for helpful discussions relating to the structure and petrology of the area, and to Dr. Ian Campbell, Chief, California Division of Mines and Geology, for a critical reading of the manuscript.

GEOLOGY OF LEECH LAKE MOUNTAIN

The rocks at Leech Lake Mountain consist of interbedded graywackes, siltstones, and cherts; sills of diabase and serpentinite; and flows of basalt. The only fossils found were a few radiolaria in the chert, and fairly well preserved *Buchia piochii* (Gabb) in the graywacke. The entire sequence is considered to be part of the Franciscan Formation (Upper Jurassic to Lower Cretaceous) which covers extensive areas in this part of California.

Figure 1.

Graywacke, ranging from massive to well bedded, is the most abundant rock type exposed in the area. Even in the massive graywacke, crude bedding is suggested by parallel rows of dark, flat fragments of shale. The graywacke, where it is distant from the serpentinite bodies and apparently unaltered, is medium gray in color; near the serpentinite contact, where it has been altered, the graywacke ranges in color from dark bluish-gray to a very light gray.

The unaltered graywacke is a dense rock consisting of about 60 percent of fragments which range from 0.5 mm to 1 cm in size. They consist of basalt, plagioclase (An35-40), black shale, augite, hornblende, and minor amounts of quartz. These fragments are enclosed in a fine-grained matrix of argillaceous material, sericite, chlorite, and devitrified volcanic ash.

Interbedded with the graywacke are thin beds of siltstone which have a smaller average grain size, and contain a higher percentage of argillaceous material and devitrified volcanic ash than does the graywacke.

Chert, composed largely of crystalline quartz with crisscrossing veinlets of microcrystalline quartz and clear chalcedony, occurs in lenses composed of well-layered beds. Its color ranges from yellowish-gray through grayish-green; brown; and red to black. Radiolarian tests and spicules are rare, but are most abundant in a red ferruginous chert.

Diabase sills occur in several parts of the area studied. They are localized primarily in two areas which are about one mile apart. On Leech Lake Mountain, at least six diabase sills were mapped in a northeast-trending zone about a mile long and a quarter of a mile wide. The sills range in thickness from six feet to 30 feet and in color from dark grayish-green to grayish-black. They are separated from each other by beds of well-layered chert. The second area, about one mile south of Leech Lake Mountain contains fewer sills, but these appear to be similar to those at the Leech Lake Mountain area.

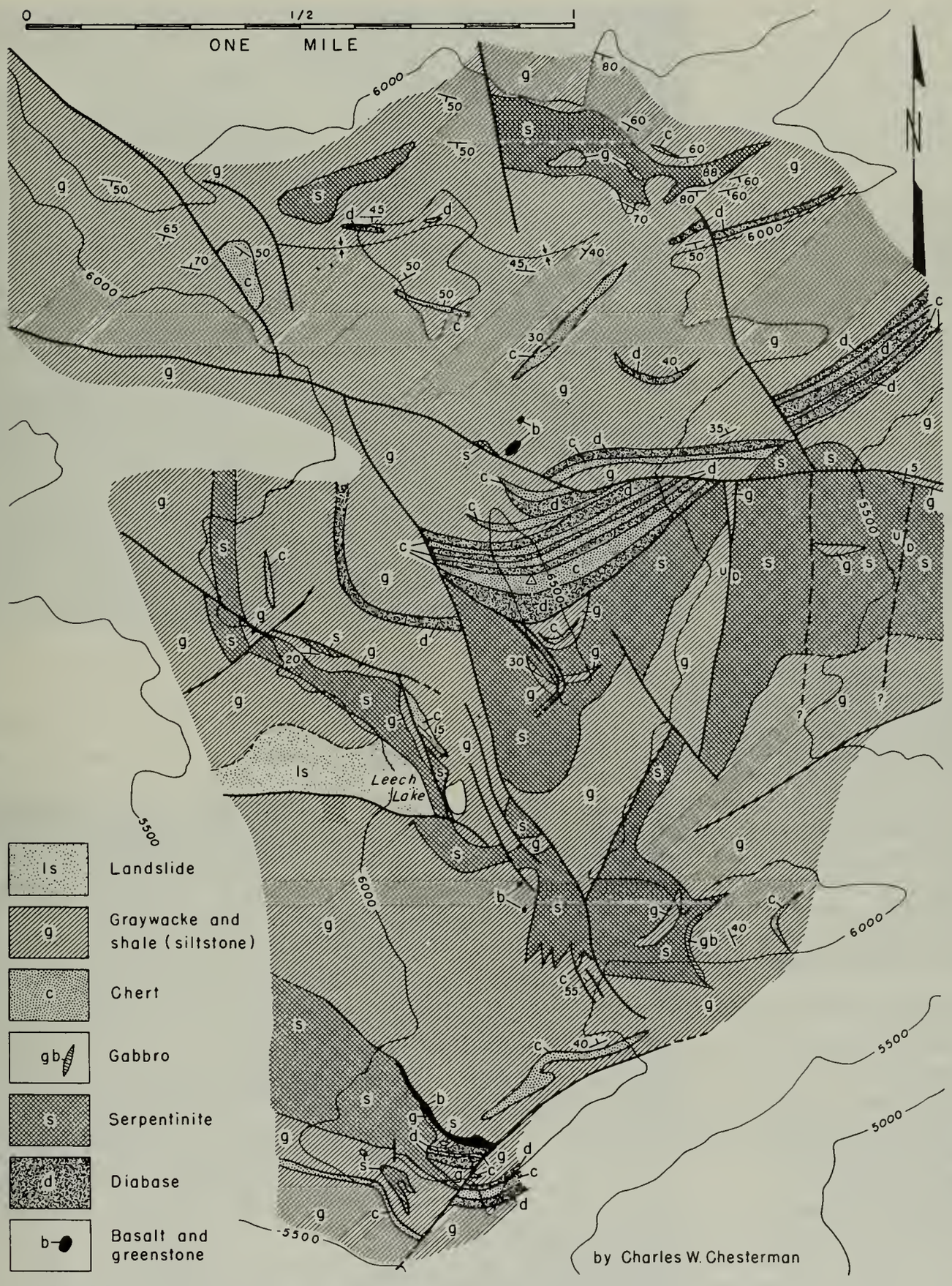
In thin section, the diabase displays an ophitic texture. Deep pink titaniferous augite occurs in conspicuous prismatic crystals which are largely altered to pale-green chlorite and actinolite, and rarely to strongly pleochroic blue crossite. Plagioclase (average composition about An 50) is altered to pumpellyite and prehnite. Granular sphene, leucoxene, apatite, and ilmenite are abundant accessory minerals.

Greenstone and basalt occur as small plug-like bodies in the graywacke and as thin flows associated with the diabase. The greenstone is dark brownish-green in color, fine-grained, and extensively fractured. Where it has been intruded by peridotite, the greenstone has been converted to a dense hornfelsic rock containing abundant actinolite, some chlorite, and green diopsidic pyroxene.

Sills of peridotite, now fully converted to serpentine rock, intrude the other rocks. The serpentinite is green, bluish-green, and brownish-green in color. The most common variety is massive, coarsely crystalline, and contains bastite. Picrite is common, especially in local areas within the bastite serpentinite. Chrysotile is present but not common. Chromite and magnetite occur in small grains, scattered sparsely throughout the serpentinite.

Small veins of white, tough rodingite are scattered throughout the serpentinite. These are composed of colorless vesuvianite, colorless hydrogrossular, prehnite, zoisite, and talc. The largest body of rodingite exhibits a coarse pegmatitic texture and appears to have been formed through hydrothermal alteration of a gabbro pegmatite. A similar origin was suggested by Grange (1927) and Bloxam (1954) for rodingite bodies in New Zealand and Scotland respectively.

Other bodies of rodingite appear to have an entirely different origin. They have almost the same mineralogy as the rodingite body just described, but contain in addition angular grains of feldspar which are largely replaced by a pale-green fibrous pyroxene; clusters of graphitic material derived from carbonaceous shale fragments; and a pyroxene composed of 70 percent diopside, 20 percent jadeite, and 10 percent acmite.



GEOLOGIC MAP OF LEECH LAKE MOUNTAIN, MENDOCINO COUNTY, CALIFORNIA

Figure 2.

Phata 1. Contact between serpentinite (s) and graywacke (g). White cantact zane (c) and veinlets in serpentinite are camposed af nephrite, diopsidic-jadeite, hydragrassular and vesuvianite. Scale is indicated by 5-inch long pencil.

The presence of quartz grains, altered feldspar, and the clusters of graphitic material indicate that the rodingite was derived from graywacke which had been engulfed in the peridotite during its emplacement. Bodies of this type of rodingite are usually less than four inches thick. Most of them contain a contact zone of serpentinized graywacke which is less than one inch wide. Under the microscope, this serpentinized graywacke is fine-grained and appears to consist largely of a pale-green, very low birefringent matrix material—some chlorite, and some antigorite—all enclosing the grains of altered feldspar and fragments of shale.

CONTACT METAMORPHISM OF THE GRAYWACKE

Contact relationships between the graywacke, chert, greenstone, and diabase, and the ultrabasic rocks that intruded them are unusually well exposed and clearly defined at Leech Lake Mountain, offering a rare opportunity to study the mineralogical and structural contact effects.

Ideally, the effects of metamorphism of the graywacke by the ultrabasic intrusion should be studied in samples taken at regular intervals away from the contact along a bed that meets the contact at right angles. At Leech Lake Mountain, this sampling technique was impossible, because the intrusive contacts are conformable with the adjacent bedding. Therefore, samples were taken in the next best way: at regular intervals perpendicular to the bedding and the contact, across the bedding of a single massive bed of graywacke about 15 feet thick.

Fifteen feet from the serpentinite contact, the graywacke is medium-gray in color and shows slight foliation parallel to the bedding. It contains angular fragments of plagioclase (An 35-40) which are partially altered to sericite; blue-green hornblende; finely fibrous, pale blue-green actinolite; basalt fragments in which the ferro-magnesian minerals are altered to pale-green chlorite; and shale. The matrix is composed of argillaceous material and devitrified volcanic ash.

Three feet from the serpentinite contact, the graywacke is medium-gray in color and shows the same foliation as it does 15 feet from the contact. The mineralogical composition of the graywacke three feet from the contact, however, shows a marked change: actinolite persists but a pale yellowish-green pyroxene of aegiritic composition has developed at the expense of the argillaceous matrix material. The shale fragments have disappeared and in their place are spongelike clusters of black grains (probably graphite).

One foot from the serpentinite contact, the graywacke is light-gray in color and still displays a clastic texture. The angular fragments of feldspar (An 35-40) are partially altered to sericite, and altered fragments of basalt and black shale are recognizable. Actinolite is even less abundant than at three feet from the contact; aegirite is still present; and blue pleochroic amphibole

(glaucophane) is present, apparently derived from clasts of pale bluish-green hornblende.

Six inches from the serpentinite contact, the graywacke is lighter still in color than that one foot from the contact. A prominent set of joints has developed, normal to the contact. Feldspar is scarce, and altered largely to minute scales of sericite. The pyroxene is diopsidic jadeite (di_{60} ja_{40}), and occurs in colorless, needle-like crystals that seem to have developed best in open cavities which later were filled with calcite. The fragments of basalt are completely destroyed; many are altered to clusters of radiating needles of diopsidic jadeite. The matrix material is recrystallized, and also contains abundant diopsidic jadeite. No blue amphibole could be found. Small, well-developed crystals of green garnet, radiating rosettes of thomsonite, some pale-green antigorite, and colorless prehnite are also present. Both the thomsonite and prehnite occur as late fracture fillings.

A metamorphic zone of mottled light-green and greenish-white material, ranging in width from a fraction of an inch to as much as 18 inches, is developed at the contact of the graywacke with the serpentinite. This material, which has a specific gravity of about 3.3, is composed of minerals derived from both the serpentinite and the graywacke, and contains in addition incompletely altered fragments of graywacke and serpentinite. The bulk mineralogy, which varies greatly from place to place in the zone, includes nephrite, diopsidic-jadeite (di_{80} ja_{20}), vesuvianite, hydrogrossular, prehnite, thomsonite, chrysotile, antigorite, and garnet. Veins that consist principally of nephrite, diopsidic jadeite, and minor amounts of vesuvianite and hydrogrossular, branch into the serpentinite from the metamorphic zone. These veins, which range from 1 mm to 30 mm in width, form a network that extends into the serpentinite as far as three feet from the contact. Veins of this composition have not been found in the graywacke; instead, one finds monomineralic veins of pectolite, xonotlite, and calcite. The pectolite veins are common but are short and few extend farther than two feet into the graywacke.

In general, the veins in the serpentinite are relatively high in calcium and magnesium, but are low in aluminum; those in the graywacke are higher in calcium, but lack aluminum and magnesium.

The distribution of the minerals in the contact zone appears to be controlled by bulk composition: vesuvianite and hydrogrossular, minerals high in calcium and aluminum, tend to be localized in the graywacke side of the contact zone; nephrite and pyroxene occur generally in the serpentinite side of the contact zone.

METAMORPHISM OF THE CHERT AND DIABASE

The chert, at its contacts with serpentinite and diabase, is a dense, fine-grained rock in which the silica has recrystallized to fine-grained quartz. Both aegirite and pale bluish-green amphibole are present. The aegi-

Photo 2. Apophyses of serpentinite (s) in graywacke (g). White veinlets in middle apophysis are composed of nephrite and diopsidic-jadeite, and are fillings along shear joints. The blunt end of the middle apophysis appears to be just an edge of the apophysis.

rite is more abundant than the amphibole and occurs in rosettes of yellowish-green crystals. The red iron oxide which is common to most cherts in this area is recrystallized to hematite.

The contact metamorphic effects of the peridotite upon the diabase, however, are more evident and intense than are those upon the chert. Titaniferous augite is completely altered to pale-green chlorite, a pale-green amphibole, and serpentine minerals. Feldspar is completely altered to a fine-grained mixture of pumpellyite and a colorless, low-birefringent material. Of all the minerals originally present in the diabase, apatite is least affected. It remains as typically cross-fractured needles, and is best preserved where it occurs in a matrix of fine-grained chlorite. The ilmenite and sphene are altered to leucoxene.

Of considerable interest is an uncommon, deep-brown, strongly pleochroic amphibole, which appears to be idioblastic where it replaces the original pyroxene, but is in xenoblastic crystals where it replaces the chloritic matrix material. From its optical qualities (negative, $2V = 75\text{-}80°$, $Z \wedge C = 16°$, X= pale yellowish-brown, Y = reddish-brown, Z = dark red-brown) and association, this mineral is referred to as kaersutite. An amphibole of similar properties and occurrence has been decribed by Bloxam (1955, p. 322).

A contact zone, rarely more than a few inches wide, is developed at the diabase-serpentinite contact. This zone consists essentially of pale-greenish nephrite, some pale-green serpentine minerals (mainly chrysotile) and talc. Very narrow veins of the same mineralogy extend from the contact zone into the diabase and serpentinite. Much of the nephrite in this zone, and in the veins, apparently formed through endomorphic effects on the peridotite at the time of its emplacement.

MODE OF EMPLACEMENT OF THE PERIDOTITE

From the mineralogical and field evidence mentioned above, it is concluded that the serpentinite was originally emplaced as a liquid magma of peridotitic composition and not as a cold intrusion of serpentinite. Intrusive contacts are common along the margins of all serpentinite bodies in this area. The upper contact of the largest sill on Leech Lake Mountain contains several small apophyses of bastite serpentinite ranging in thickness from 12 inches to four feet. The smaller apophyses effected a lower degree of metamorphism on the enclosing graywacke than did the larger serpentinite bodies. At its contact with the apophyses, the graywacke is bleached light-gray and is cut by tension joints normal to the contact. The apophyses are cut by a conjugate system of shear joints which are filled with veins of nephrite and diopsidic jadeite. The mineralogy of the graywacke at its contact with the apophyses is the same as that of the graywacke in contact with the larger serpentinite bodies.

The graywacke at and near the larger serpentinite bodies is not strongly deformed and contorted but is prominently jointed parallel to the bedding. The serpentinite is not sheared intensely at the contact. It is believed, therefore, that the original peridotite was sufficiently mobile to be forcefully emplaced along bedding planes in the graywacke and that the graywacke was indurated, yet sufficiently plastic to allow the peridotite access.

GRADE OF METAMORPHISM

The graywacke has undergone progressive contact metamorphism, with progressively higher grades being found towards the contact with the intruding peridotite. The mineral assemblage in the altered graywacke at the contact consists of diopsidic jadeite, scarce glaucophane (and/or crossite), antigorite, and chlorite. Although this assemblage is not necessarily characteristic of the glaucophane schist facies, the presence of considerable diopsidic jadeite and scarce glaucophane indicates that the grade of metamorphism has progressed beyond the greenschist facies and is transitional into the glaucophane schist facies. Metamorphic conditions within the glaucophane schist facies—namely low temperature and high pressure (Turner, 1958, p. 226; Bloxam, 1956, p. 496)—would surely account for the formation of the diopsidic jadeite.

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GEOLOGY OF THE SEDIMENTARY DEPOSITS IN SAN FRANCISCO BAY, CALIFORNIA*

By RAY C. TREASHER

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ABSTRACT

Studies of the sediments in San Francisco Bay show that these deposits accumulated to thicknesses in excess of 300 feet. The deposits are principally clay and silt, with minor lenses of sand and gravel. The grain size of the sediments is fairly uniform both perpendicular to and parallel with the bedding. The informal stratigraphic units used in this report differ primarily in their degree of preconsolidation, density, and compressive strength. Contours on the upper surface of bedrock, the older bay mud and the upper member of the younger bay mud indicate that all have been eroded to produce considerable relief.

The older bay mud and the semi-consolidated member of the younger bay mud are preconsolidated to a density greater than would be expected from the weight of the overlying sediments. These units are overlain by a normally consolidated member of the younger bay mud. It is postulated that the preconsolidation was caused by desiccation in air resulting from fluctuations in sea level. These changes in sea level may have been caused by the repeated storage and release of sea water in glacial ice.

INTRODUCTION

San Francisco Bay, one of the finest salt-water harbors on the Pacific Coast, lies in a northerly trending intra-montane valley in the central Coast Ranges of California. This valley includes Petaluma Valley and Napa Valley to the north and Santa Clara Valley to the south. San Francisco Bay, which lies within the valley, includes three main parts: South San Francisco Bay; North San Francisco Bay; and San Pablo Bay. Suisun Bay to the east connects with San Pablo Bay through Carquinez Strait (Figure 1).

Fresh water enters San Francisco Bay principally from the Sacramento and San Joaquin Rivers which drain the Central Valley of California through Carquinez Strait. During the flood stages of late winter and early spring, enormous volumes of fresh water from these rivers pass through San Francisco Bay and are wasted to the ocean. In order to conserve some of this water, and for other reasons, a series of plans has been proposed to construct barriers across the bay at various positions. The most widely publicized of these plans was the Reber Plan proposed by the late John Reber.

In 1955, the State of California published the results of office-engineering studies of the various proposed plans with estimates of the lowest costs of constructing and maintaining these projects (Division of Water Resources, 1955). About 1957 Congress authorized the U. S. Army Engineer District, San Francisco, to perform field and office studies of the feasibility and engineering problems involved in the construction of these projects. Undisturbed cores were obtained from ten deep drill holes drilled between the Richmond-San Rafael Bridge and the San Francisco-Oakland Bay Bridge, and logs of over 3,000 drill cores from various governmental and private agencies were assembled and studied. Data from these sources largely formed the basis of the information presented herein.

ACKNOWLEDGMENTS

These studies were made by members of the staff of the Foundations and Materials Branch, San Francisco District, Corps of Engineers; D. C. Johnson, H. E. Pape, Robert Riddle, I. C. Campbell, Nobuscu Shimezu, R. C. Thompson, Ron Gelnet, William Angeloni, and the writer. John L. Burnett and Harold B. Goldman of the California Division of Mines & Geology edited and prepared the manuscript for publication. To these, the writer wishes to make grateful acknowledgement of all the assistance given. He also wishes to state that the conclusions presented herein do not necessarily reflect the opinion of the Corps of Engineers and he assumes full responsibility for all statements.

* Presented at the Le Conte Geological Club, San Francisco, California on December 2, 1961.

122°30'
122°15'
122°00'
SAN PABLO BAY
Ryer Island
Simmans Island
Suisun Bay
Hanker Bay
Van Sickle Island
Carquinez Strait
38°00'
38°00'
Pt. San Pedra
A
A'
Pt. San Pablo
B
B'
Corte Madera Creek
RICHMOND
Richmond - San Rafael Bridge
Southampton Shoals
Richardson Bay
ALBANY
North San Francisco Bay
BERKELEY
Pt. Knox
Angel Island
EMERYVILLE
Treasure Island
C'
San Francisco - Oakland Bay Bridge
OAKLAND
EXPLANATION
AREA OF SAMPLING
5
0
5
10 MILES

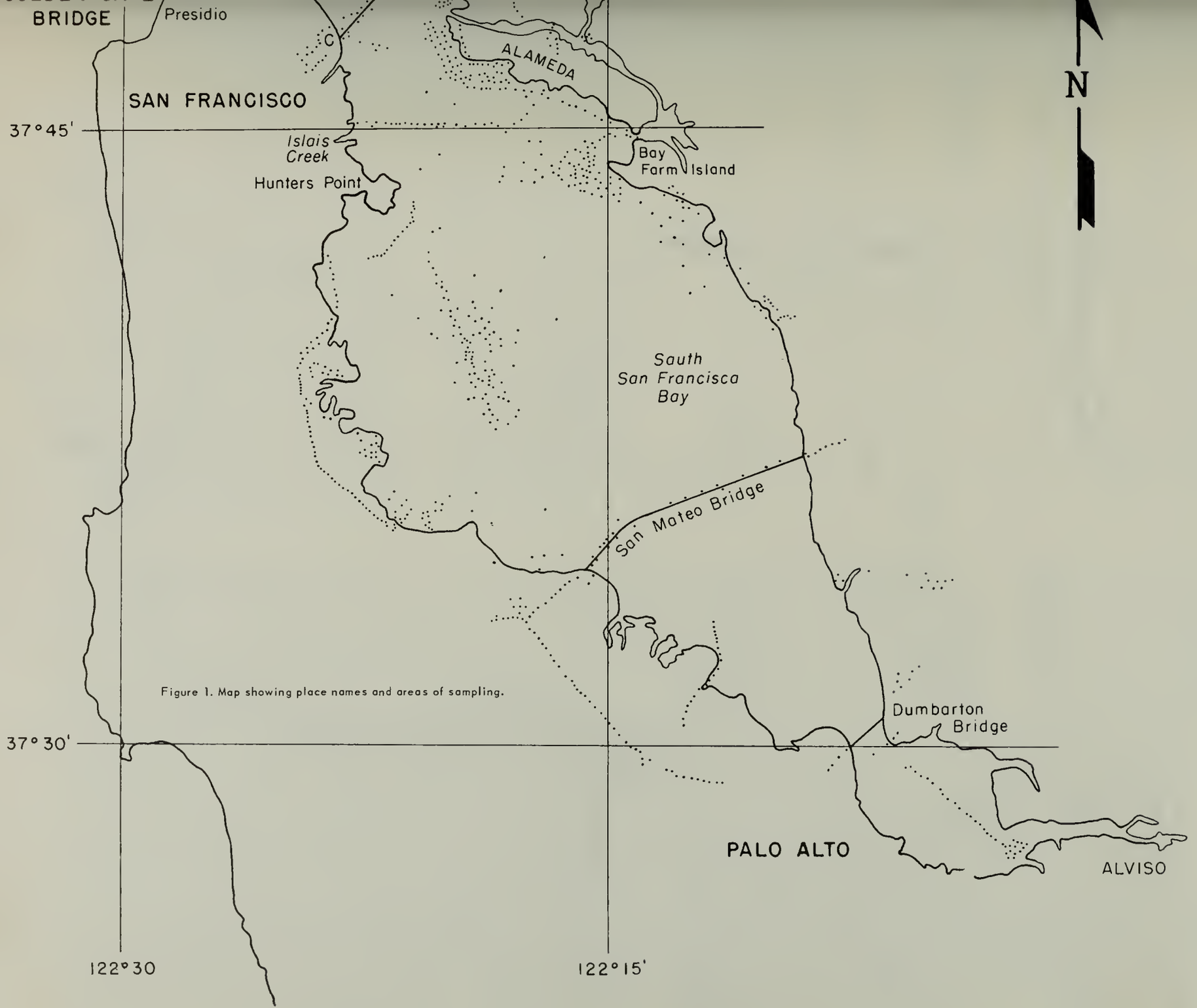


Figure 1. Map showing place names and areas of sampling.

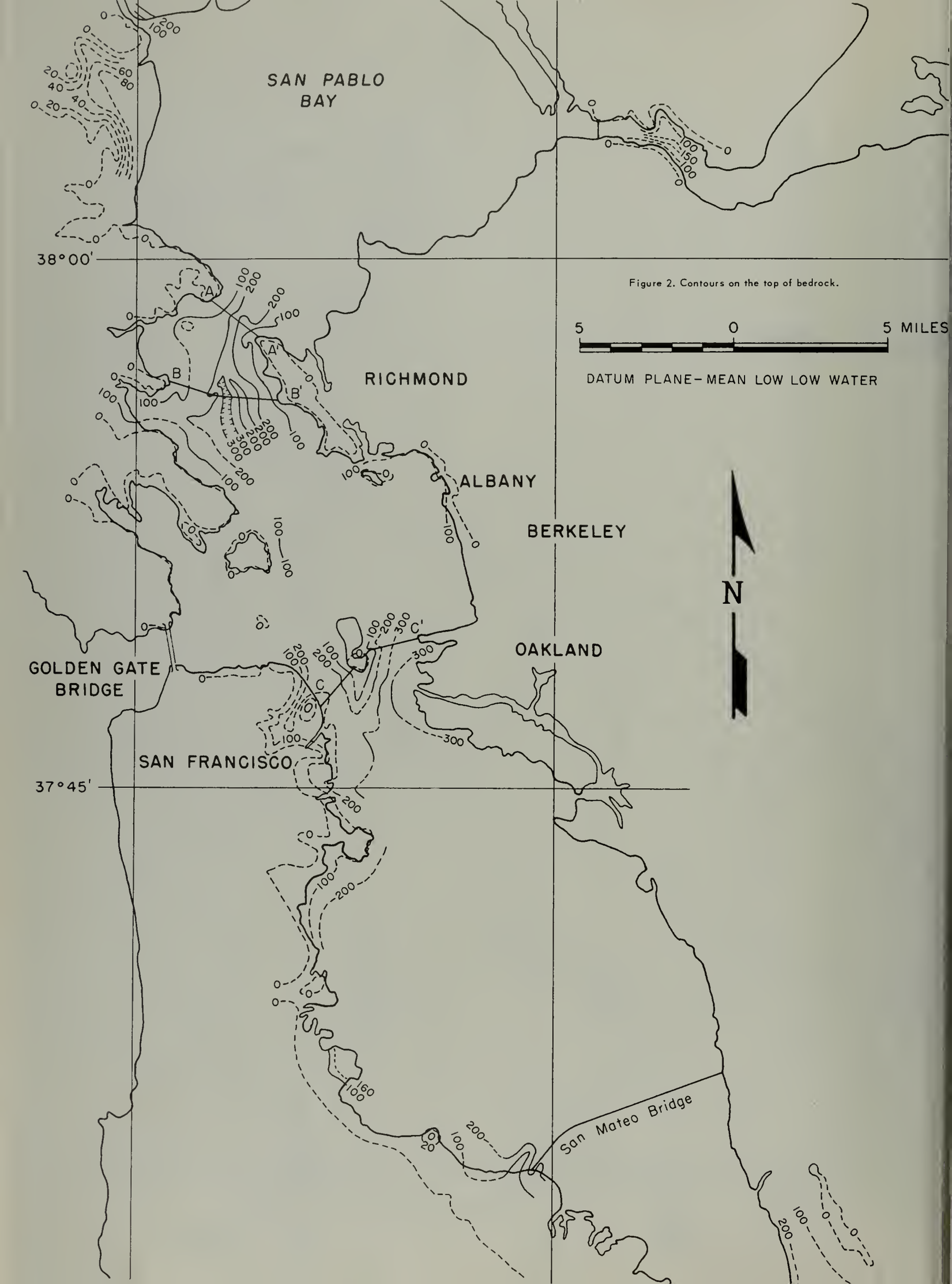


Figure 2. Contours on the top of bedrock.

Table 1. Correlation chart of sediments of San Francisco Bay.

Lawson, A. C. (1914)	Trask, Parker, and Rolston, J. W. (1951)	Present studies by Corps of Engineers	
BAY MUD	BAY MUD Formation A Member A-1 A-2 A-3	YOUNGER BAY MUD	SOFT MEMBER
			SEMI-CONSOLIDATED MEMBER
MERRITT SAND	MERRITT SAND Formation B Member B-1 B-2	SAND DEPOSITS (including Merritt sand)	
SAN ANTONIO FORMATION	POSEY FORMATION Formation C Member C-1 C-2	OLDER BAY MUD	
	SAN ANTONIO FORMATION Formation D Member D-1 D-2 D-3		
ALAMEDA FORMATION	ALAMEDA FORMATION Formation E		
BEDROCK	BEDROCK	BEDROCK	
(Bedrock is principally Franciscan Formation)			

SEDIMENTS WITHIN THE BAY

The geology of San Francisco Bay and the sedimentary deposits within the Bay were discussed by Lawson (1914), Trask and Rolston (1951), and Louderback (1951); a correlation chart of the sedimentary deposits is presented on Table 1. The areal geology of the region is shown on the Santa Rosa sheet (Koenig, in press, 1963), and the San Francisco sheet (Jennings and Burnett, 1961) of the Geologic Map of California.

The bedrock in this area consists primarily of graywacke, black shale and slate, greenstone, and chert of the Franciscan Formation which is of Upper Jurassic to Cretaceous age. In San Francisco Bay, fine-grained sedimentary deposits of Pleistocene to Recent age have accumulated to thicknesses of over 300 feet. These sedimentary deposits are principally clay and silt, with minor lenses of sand and gravel. The deposits generally are uniform in grain-size and mineralogy throughout their thickness; the principal differences between the units used in this report are degree of consolidation and stratigraphic position. Based on these differences, the sedimentary deposits are divided into an older bay mud, sand deposits, and a younger bay mud. The younger bay mud is subdivided into a semi-consolidated member which is overlain by a soft member. The units described by Trask and Rolston (1951) were not found to be applicable during the course of this investigation. The geologic names in this report are used only for convenience and are not being formally proposed.

The known configuration of the top of bedrock (figure 2), the top of the older bay mud (figure 3), and the top of the younger bay mud (figure 4) have been used to prepare cross-sections across the Bay from Point San Pedro to Point San Pablo, the Richmond-San Rafael Bridge and the San Francisco-Oakland Bay Bridge (figure 5).

OLDER BAY MUD

The older bay mud is a stiff to very stiff, firm clay, which contains varying amounts of silt, and lenses of sandy clay, sand and gravel. When plotted from data supplied by drill logs, the lenses did not readily lend themselves to correlation. Schlocker and others (1958), and Radbruch and Schlocker (1958) determined that the minus two-micron sizes are 50 percent normal and hydrated mica, plus montmorillinite, chlorite, diatoms, carbonaceous material, quartz, and feldspar. The grain-size of materials near the shore is strikingly similar to the grain-size of materials from deep beneath the waters of the bays. The older bay mud is preconsolidated to a degree greater than would result from the weight of the overlying sediment.

The older bay mud ranges from less than one foot to over 200 feet in thickness; in some places it is missing along the margins of the bay and it thickens toward the central portion of the bay. The surface of the older bay mud is eroded deeply (figure 3), indicating that a major stream drainage network probably was established at a time when the upper surface of the older bay mud was at or near sea level.

The buried drainage network crosses Suisun Bay as a channel beneath Van Sickle Island and Honker Bay, and then passes between Ryer Island and Simmons Island. It then trends southwestward, along the west shore, through Carquinez Strait. Data are not available for the reach through San Pablo Bay. The channel continues southward between Point San Pedro and Point San Pablo and through the western side of North San Francisco Bay at depths of more than −140 feet M.L.L.W. (M.L.L.W. is mean lower low water, the base for hydrographic measurements instead of sea level, which is the base for terrestrial measurements). Tributaries reach eastward to head near Albany, Emeryville, the Southern Pacific mole and the Inner Harbor north of Alameda. Two channels reach westward, one toward Corte Madera Creek and one through

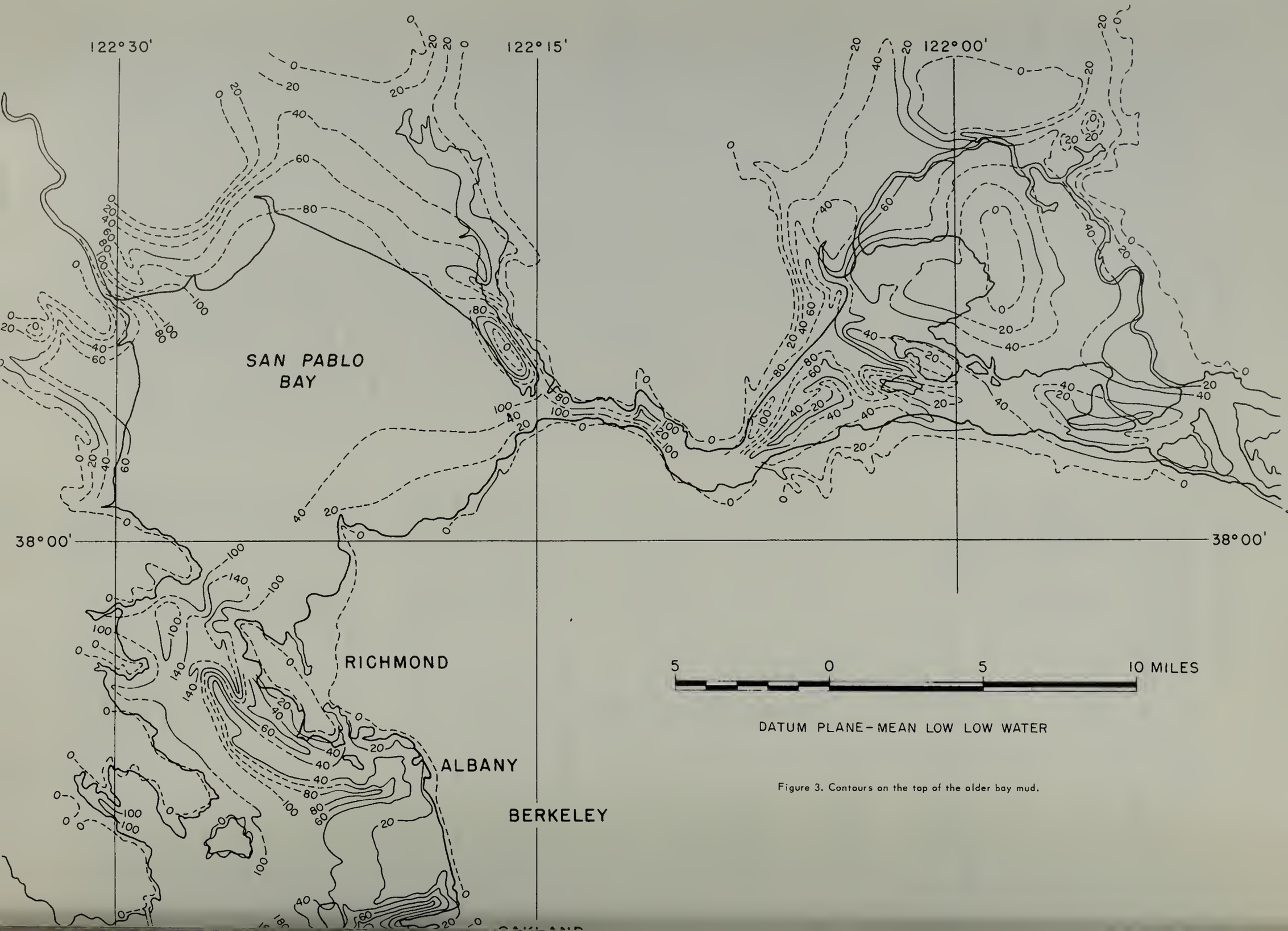
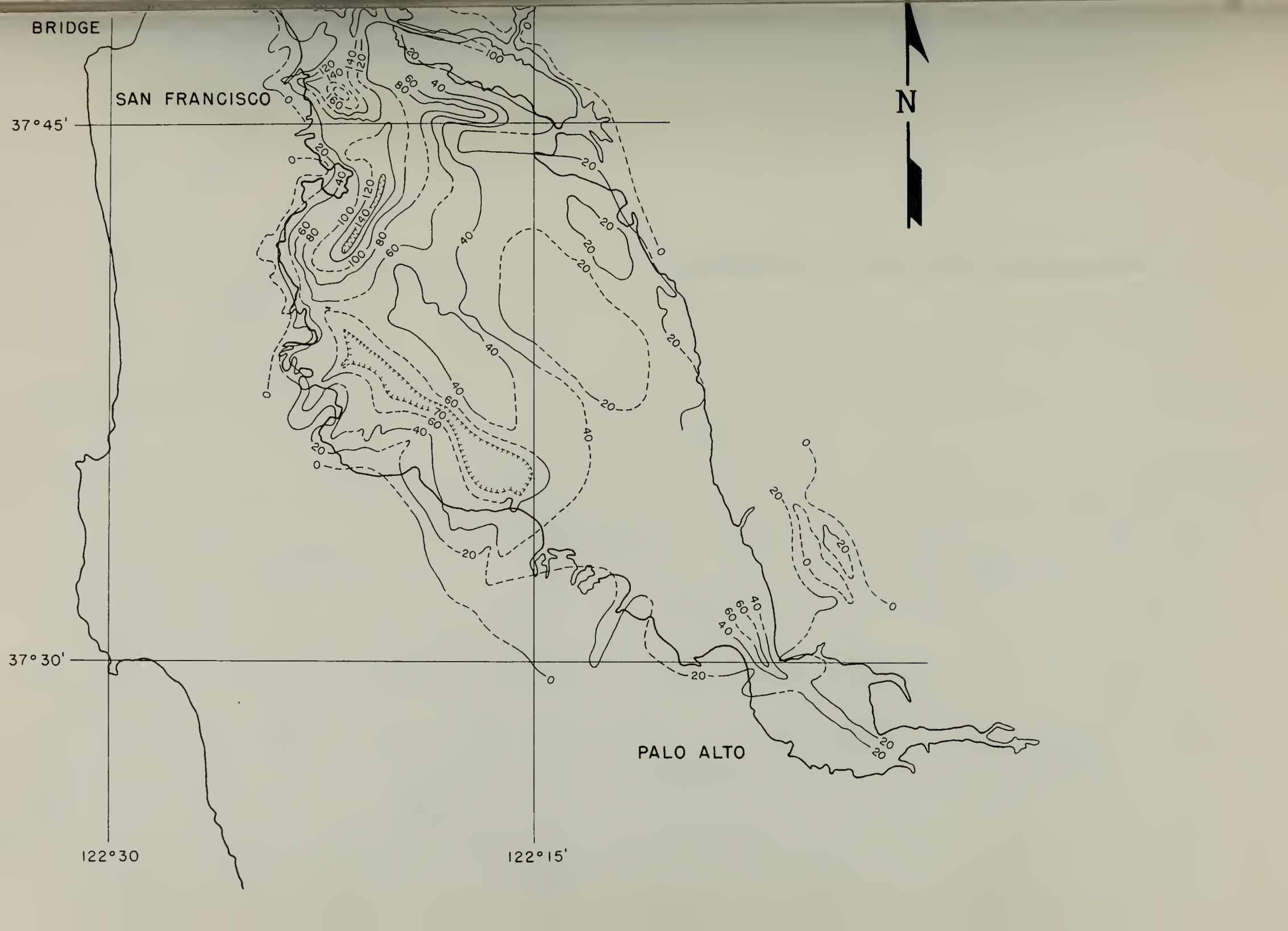


Figure 3. Contours on the top of the older bay mud.


BRIDGE
SAN FRANCISCO
37°45'
37°30'
122°30
122°15'
PALO ALTO
N

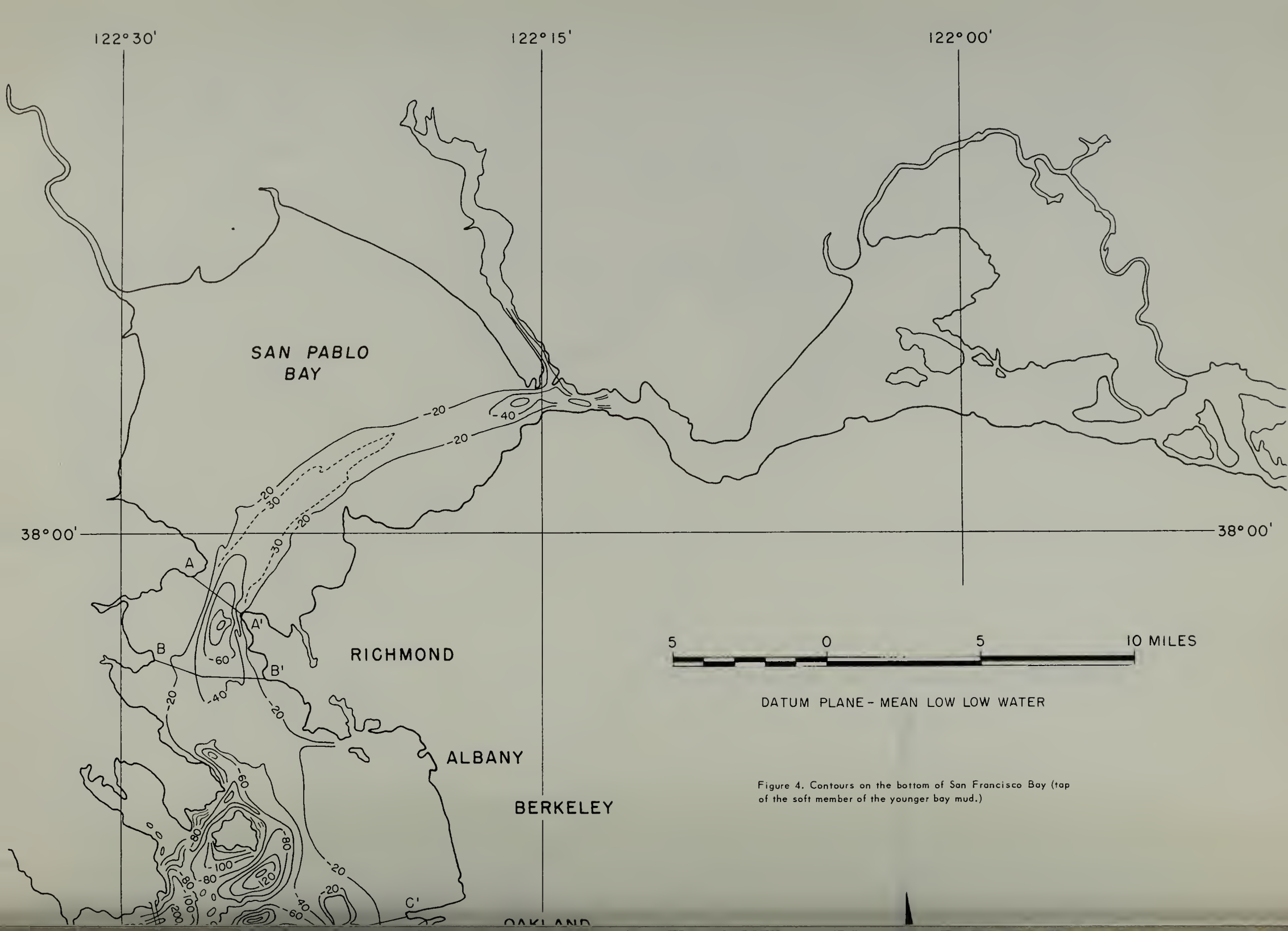
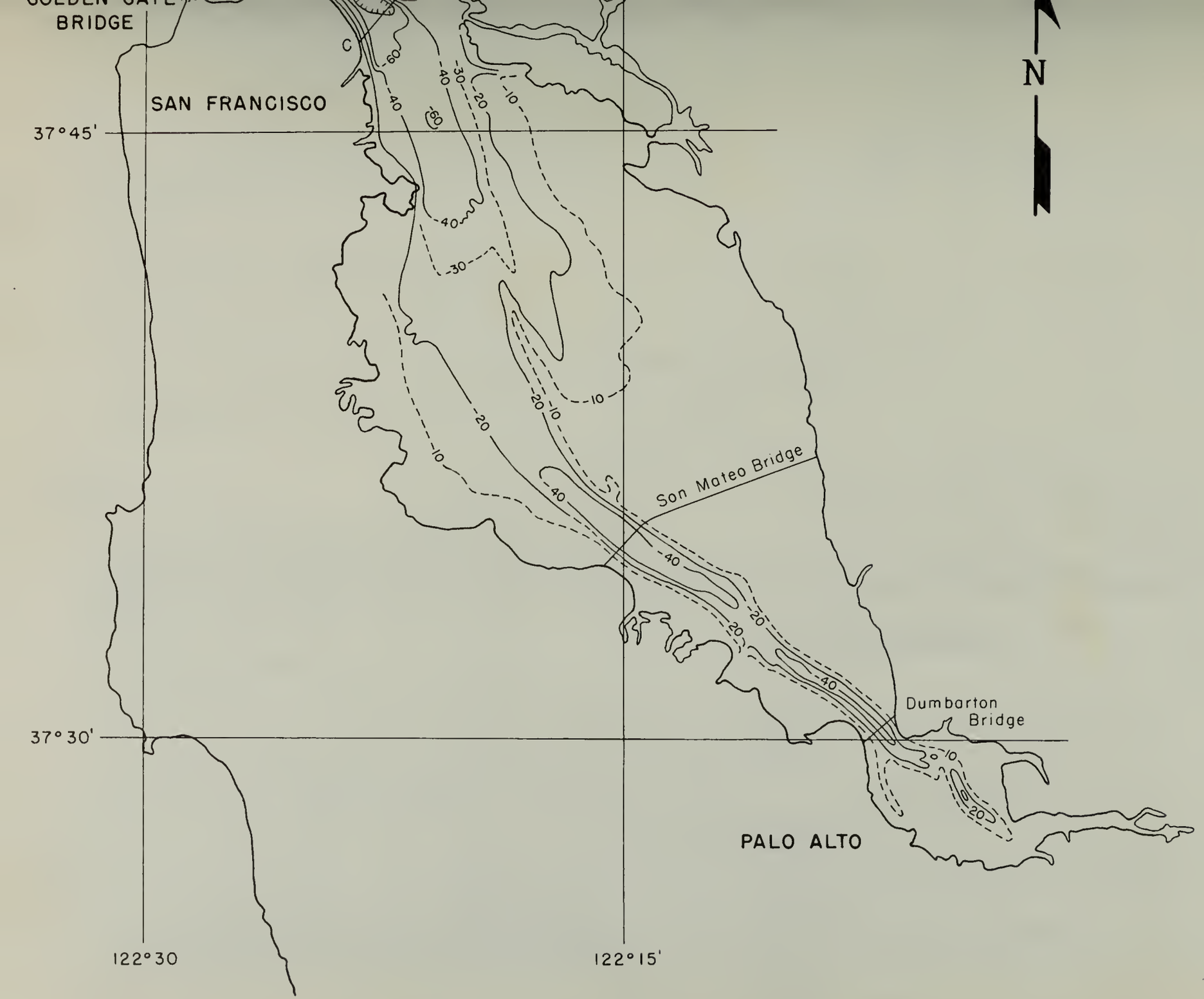
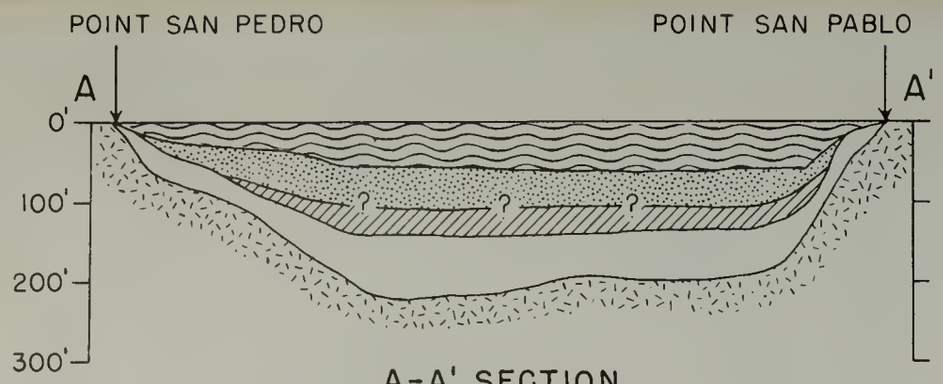


Figure 4. Contours on the bottom of San Francisco Bay (tap of the soft member of the younger bay mud.)


GOLDEN GATE
BRIDGE
SAN FRANCISCO
37°45'
37°30'
122°30
122°15'
N
San Mateo Bridge
Dumbarton
Bridge
PALO ALTO
60
40
30
20
10



A-A' SECTION
POINT SAN PEDRO - POINT SAN PABLO

EXPLANATION

WATER

SOFT BAY MEMBER

SEMI-CONSOLIDATED MEMBER

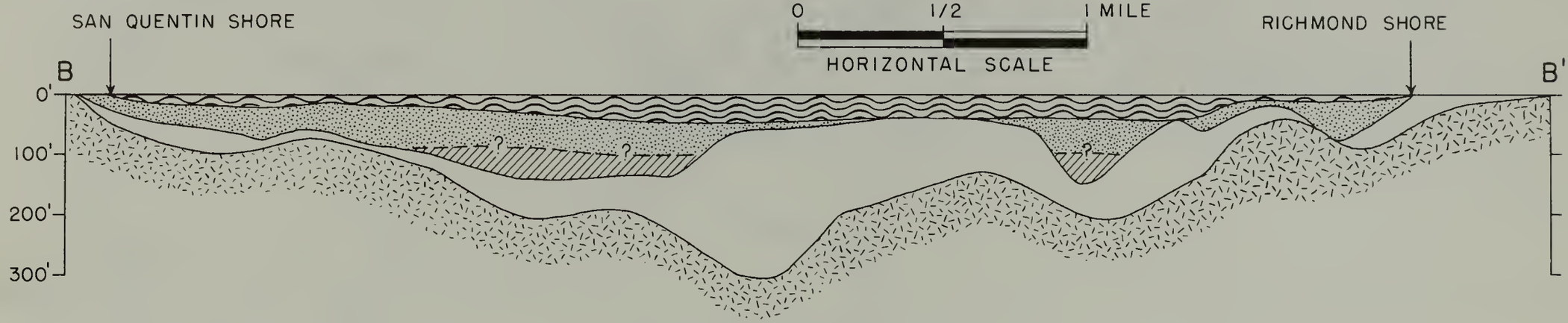
YOUNGER BAY MUD

OLDER BAY MUD

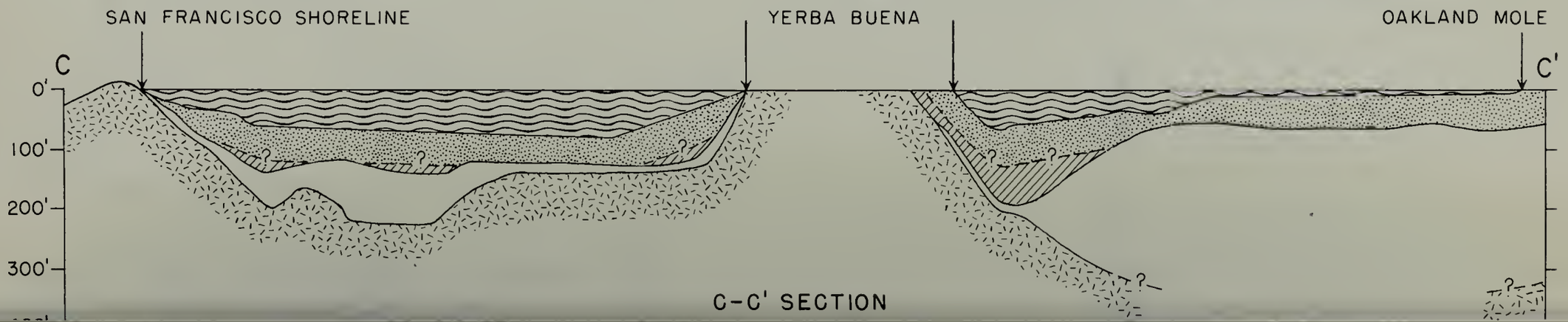
FRANCISCAN-TYPE BEDROCK

0 1/2 1 MILE

HORIZONTAL SCALE



B-B' SECTION
RICHMOND-SAN RAFAEL BRIDGE



C-C' SECTION

Table 2. Engineering properties of sediments of the San Francisco Bay.

PROPERTIES	OLDER BAY MUD	YOUNGER BAY MUD	
		Semi-Consolidated Member	Soft Member
Degree of preconsolidation	Greater than weight of overlying sediments and greater than that of semi-consolidated member	Greater than weight of overlying sediments and greater than that of soft member. Preconsolidation is about one-half that of the underlying older bay mud	Normal consolidation
Increase in density on drying	High dry density (stiff to very stiff clay). Density is greater than semi-consolidated member	Marked decrease in dry density (as compared to the older bay mud) at the rate of 10 to 25 lbs. per cu. ft.	Less than 10 lbs. per cu. ft.
Average water saturated weight	131 lbs. per cu. ft.	110 lbs. per cu. ft.	97 lbs. per cu. ft.
Average weight submerged in water	68 lbs. per cu. ft.	47 lbs. per cu. ft.	34 lbs. per cu. ft.
Average moisture content	Less than 40 percent	About 40 percent	Greater than 40 percent
Compressive strength	1,000 to 4,000 lbs. per sq. ft.	1,000 lbs. per sq. ft.	200 lbs. per sq. ft. Strength is a function of pure cohesion and no coefficient of friction exists
Foundation characteristics	GOOD Foundation for piles and other similar structures, and for all but heavy, concentrated load	FAIR Foundation for earthfill having a broad base. Not good for piles or other similar structures	POOR Piles, and other similar structures tend to sink of their own weight
Special properties			Sensitive clay. Swells when wet, tends to desiccate when dried in air
			Highly compressible
			Loses 50 percent of strength when disturbed. Regains strength due to thixotropic action
Origin	Results from flocculation of clay colloids in salt water. Tends to deflocculate when placed in fresh water		
Thickness	Up to 200 feet	Up to 60 ft., 40 ft. average	Up to 70 ft., 60 ft. average
Physical properties and mineralogy	Firm clay with varying amounts of silt and lenses of sandy clay, sand and small-sized gravel. Minus 2-micron sizes are 50 percent normal and hydrated mica; plus montmorillonite, chlorite, diatoms, carbonaceous material, quartz, feldspar. (Schlocker and others 1958)	Plastic, silty clay, and clayey silt, with varying amounts of organic matter, clayey fine-grained sand, and some shell lenses. Clay sizes are 45 to 90 percent of total; ⅓ normal and hydrated mica; ⅓ montmorillonite, and ⅓ mixed-layered montmorillonitic, chloritic, and kaolinitic material. Less than 5 percent carbonaceous material. (Schlocker and others, 1958)	

Richardson Bay. A deep "hole" lies southeast of Treasure Island. The channel trends toward the Golden Gate between Treasure Island and San Francisco. In South San Francisco Bay, one tributary reaches westward up Islais Creek and one eastward south of Alameda. The main channel trends southerly past Hunters Point to the western edge of the San Mateo Bridge at depths of −70 to −180 feet. The channel continues southeasterly toward Alviso at a depth of −60 feet at the Dumbarton Bridge. The location of this buried drainage network closely approximates the location of channels cut in bedrock (figure 2).

SAND DEPOSITS

A discontinuous zone of fine-grained sand overlies portions of the older bay mud. Where present, the sand deposits tend to be thicker at the south end of the Bay and thinner to the northward. The deposits are thicker near the margins of the Bay and thinner near the center. The grain size is fairly constant from the margins to the center of the Bay. Thick deposits of sand have accumulated at Bay Farm Island, Southampton Shoals, near Point Knox on Angel Island, and off the Presidio shore. Logs of drilling in these areas show a variable thickness of sand and logs of several

Photo 1. Richordson Boy, on orm of Son Froncisco Bay. *Photo by Aerophotographers, Sousolito.*

holes from any one locality do not all show the presence of sand. However, the field classification of fine-grained sediments is not exact and a drilling inspector may classify the same materials as sand, silty sand, sandy silt, or even sandy clay. But as the drilling logs are the only available data with which to interpret the presence of this unit, its erratic distribution may be due to inconsistencies in the terminology used on these logs. The known distribution of the sand deposits is so erratic that the drawing of contours on top of this unit is impractical.

YOUNGER BAY MUD

The younger bay mud is the uppermost unit in San Francisco Bay, overlying the older bay mud and sand deposits, where the latter unit is recognized. It is soft to slightly pre-consolidated, plastic and black to gray in color. The younger bay mud consists of silty clay and clayey silt with minor amounts of organic material; clay-rich, fine-grained sand; and some shell lenses. The grain-size of material near the shore is strikingly similar to material from beneath the waters of the Bay. According to Schlocker and others (1958), the clay-sized particles are 45 to 90 percent of the total volume and peaty or lignitic material is 5 percent. The clay minerals present are approximately equal amounts of normal and hydrated mica; montmorillonite; and mixed-layer clays composed of montmorillonite, chlorite, and kaolinite. The younger bay mud is classed as sensitive clay which is plastic and swelling when wetted and tends to shrink, harden, and desiccate when dried. It is absent inland but offshore is as much as 100 feet thick.

Based on the engineering properties of the sediments (Table 2), the younger bay mud is subdivided into a semi-consolidated member which is overlain by a normally consolidated soft member.

The semi-consolidated member is distinct from the soft member in that it is preconsolidated to a degree greater than would result from the weight of the overlying sediments but the amount of preconsolidation is considerably less than that of the older bay mud. This member ranges in thickness up to 60 feet.

The soft member displays normal consolidation and ranges in thickness from less than one foot to 70 feet. This member contains many lenses of shell fragments but these lenses are discontinuous and can seldom be correlated between drill holes. The top of the soft member, which forms the bottom of San Francisco Bay, is deeply eroded but this erosion is not as deep as that found on the top of the older bay mud. The trend of channels in the top of the soft member is similar to those in the older bay mud except in Suisun Bay where the channel in the soft member is near the south shore. The position of this channel in Suisun Bay and San Pablo Bay may be modified by dredging operations that maintain the navigation channel for shipping.

ENGINEERING PROPERTIES OF THE BAY SEDIMENTS

The engineering properties of the older bay mud and the younger bay mud are summarized on Table 2. The table shows that the sediments are lithologically similar and that separation into the informal units used herein is based largely on engineering properties.

PRECONSOLIDATION OF THE BAY SEDIMENTS

Although it has long been known that the sediments in San Francisco Bay gradually increase in density with depth, Radbruch and Schlocker (1958) were the first to recognize that certain portions of the bay muds have been preconsolidated to a degree greater than could be expected from the weight of the overlying sediments. Preconsolidation is discussed by Krynine and Judd (1957, pp. 156-157, see also pp. 133-136); they mention weight of overburden and moving ice sheets, desiccation, and chemical action as agents which can produce the observed compaction of preconsolidated sediments. Beginning in 1957, studies by the soils engineers of the U. S. Army Engineer District, San Francisco, proved the presence of at least two clearly distinguishable periods of preconsolidation which are represented by the older bay mud and the semi-consolidated member of the younger bay mud (Table 2).

The observed preconsolidation in the sediments of San Francisco Bay could have been caused by vibrations due to earthquakes, or by exposure of the sediments to air drying through diastrophic elevation and depression of the land surface, or through fluctuations in sea level. Preconsolidation due to earthquake activity seems unlikely because earthquake vibrations in historic times have not preconsolidated the soft member of the younger bay mud. Unless the intensity of earthquakes was greater and more concentrated in former epochs than in the historic past, there is no indication that earthquake vibrations could have produced the required amount of preconsolidation. Diastrophic elevation and depression of the land surface also does not seem to be a satisfactory answer (Louderback, 1951) and would require multiple cycles of depression below sea level to deposit the sediments and elevation above sea level to produce preconsolidation by drying. The third possibility of fluctuating sea level to expose the mud to desiccation seems most likely. Louderback (1951) proposed this mechanism to account for the drowning of the valley which presently contains San Francisco Bay. He suggested that during the last continental advance of Wisconsin glaciation, moisture was locked in the ice cap and sea level was lowered ap-

preciably, thereby allowing the Bay valley to be eroded. When the ice-sheet melted and returned water to the oceans, sea level was raised in the order of 350 feet flooding the Bay valley and allowing the sediments to be deposited.

The hypothesis of Louderback (1951) requires only one flooding of the Bay valley but if desiccation produced at least two preconsolidated sedimentary deposits, the Bay valley must have been flooded three times and partly drained twice since it was formed by erosion. A modification of this hypothesis is herein proposed that accounts for the observed preconsolidation by three separate glacial advances. The first glacial advance lowered sea level and allowed the Bay valley to be eroded. The first flooding of the valley was to a depth of at least 200 feet to allow deposition of soft mud which now is the older bay mud. The second glacial advance exposed the older bay mud to desiccation and resulted in preconsolidation. When this ice sheet melted, the Bay valley was again flooded to a depth of at least 40 feet greater than before to inundate the older bay mud and to permit the sand deposits and semi-consolidated member of the older bay mud to be deposited. The third glacial advance caused withdrawal of sea water for a shorter time than before to produce a lesser degree of desiccation and preconsolidation in the semi-consolidated member than is found in the older bay mud. The third and final flooding was to a depth of at least 60 feet more than any previous flooding and allowed the soft member of the younger bay mud to be deposited. The soft member is normally consolidated and therefore it has not been exposed to later desiccation. The three glacial advances may represent the Illinoian Glaciation and two advances in the Wisconsin Glaciation; the ages of the San Francisco Bay sediments are not known well enough to allow an exact age correlation.

At one time during the present epoch of flooding, sea level must have been as much as ten feet higher than at the present because remnants of bay mud are found at 10 feet of elevation all around the margins of the Bay. Sea level must also have been slightly lower at one time as evidences of shell mounds and of occupancy by man are found three to 18 feet below the present sea level (Louderback, 1951, p. 87). Whether these differences in sea level are due to withdrawal of water into glacial ice or diastrophic movement is not known.

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ENGINEERING PROPERTIES AND PROBLEMS OF THE SAN FRANCISCO BAY MUD*

By JAMES K. MITCHELL

Associate Professor of Civil Engineering, University of California, Berkeley

ABSTRACT

The very low strength and high compressibility of San Francisco Bay mud make this deposit the most troublesome of the San Francisco Bay sediments from a soil mechanics and foundation engineering standpoint. In addition, the geologic history of San Francisco Bay has resulted in large local variations in thickness of the mud deposit. These characteristics give rise to engineering problems in connection with supporting capacity, large total and differential settlement of structures, pile support and down-drag on piles caused by consolidating clay. With the aid of careful exploration and testing programs and appropriate soil mechanics analyses, the detrimental effects of these poor foundation conditions can be minimized.

INTRODUCTION

A great many of the foundation problems in and around San Francisco Bay relate directly to the presence of a thick layer of soft mud, known locally as bay mud, which consists of silty clay containing small amounts of sand. The bay mud is the uppermost of the five main sedimentary units of late Quaternary age that overlie bedrock. Bay mud deposits are continuing to accumulate from the sediments carried into the Bay; at the same time, erosion, transportation, and redeposition of the mud is continually in progress.

The geology of San Francisco Bay and the influence of this geology on engineering problems has been discussed by Trask and Rolston (1951) and Trask and Seed (1954). A brief summary of the geological history as discussed in these papers, is presented here, because one of the most bothersome engineering problems associated with the bay mud—that of variable stratum thickness—relates directly to this history.

SEDIMENTS OF SAN FRANCISCO BAY

The five main sedimentary units overlying bedrock in San Francisco Bay, listed from bedrock up, are:

1. Alameda Formation—this formation varies from very firm clay through sandy clay to sand and gravel. It ranges from less than 1 foot to 200 feet in thickness and is generally a good foundation material. The caissons for the section of the Bay Bridge between Yerba Buena Island and Oakland are founded on the Alameda Formation.
2. San Antonio Formation—this consists of a sequence of moderately firm clays, sands and gravels between 15 and 120 feet in thickness.
3. Posey Formation—a mixture of sand and sandy clay as much as 50 feet in thickness that is a good foundation material.
4. Merritt Sand—windblown sand up to 60 feet in thickness.

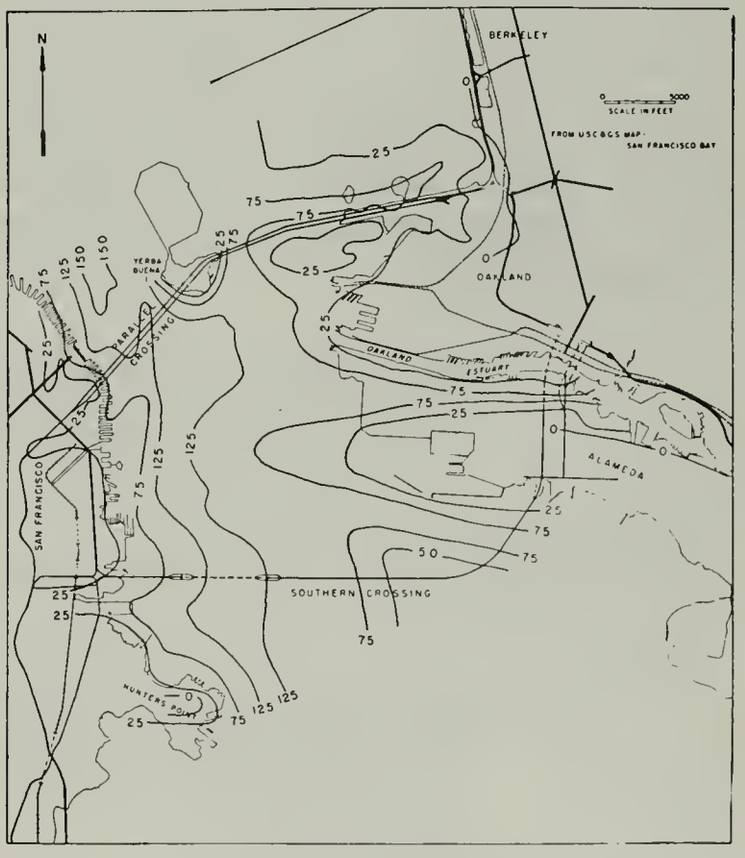


Figure 1. Contours on the base of the San Francisco Bay mud (feet below mean lower low water). After Trask and Rolston, 1951.

* Presented at the Le Conte Geological Club, San Francisco, California on December 2, 1961.

Table 1. Engineering properties of San Francisco Bay mud.

Location	Reference	Thickness of mud (feet)	Natural water content (percent)	Liquid limit (percent)	Plastic limit (percent)	Unit weight lb/ft³	Mean diameter D_{50} in microns	Shearing strength lb/ft²	Compression index C_c
Proposed southern crossing	Trask and Rolston (1951)	0–45				94–107	1.4–10.5		
Proposed parallel crossing	Trask and Rolston (1951)	0–65	35–80	47–68	--	93–113	3.7–13.5	200–400	--
Oakland Estuary	Trask and Rolston (1951)	0–45				96–101	3.6– 5.8		
Adjacent to Bridge Oakland Mole	Seed and Reese (1957)	20	35–50	41.5	23.5	112	--	100–500	0.36–0.45
Islais Creek Basin	Lee (1953)	128	52–62	--	--	102–107	--	100–1000	--
Hamilton Air Force Base	Univ. of Calif. Files	--	82–92	91	29	93–96	--	400–1200	1.1
Candlestick Cove	Private Communication	>65	50–75	65–119	28–35	98–108	2–10	150–800	0.5–1.0

5. Bay mud—the bay mud has been divided into three members by Trask and Rolston (1951).
   Member A-3. Silty clay, firmer and less sandy than zone A-1, from less than 1 foot to 45 feet in thickness.
   Member A-2. Fine to medium-grained silty sand, up to 40 feet in thickness.
   Member A-1. Soft mud as much as 65 feet in thickness composed of silty clay and occasional interbedded thin sand layers.

The Alameda, San Antonio, and Posey Formations are predominantly alluvial deposits formed above sea level, and they consist of material washed in from surrounding hills. At times during their formation, the area was flooded by the sea and a few layers of marine clay were deposited between the alluvial deposits. The sea level than sank 200 to 300 feet. Valleys—up to 150 feet in depth and 1000 feet in width—were then eroded in the deposits. Then windblown Merritt Sand partly filled these valleys and was deposited on some of the flat land between the valleys. The sea level then rose gradually to its present elevation with the resulting deposition of bay mud, which fills up the old valleys and forms a blanket over the entire area. Thus, the thickness of the bay mud varies considerably; in the filled valleys the mud may be 100 feet thick, and in the flat areas between valleys, it may be only 10-20 feet thick. Contours of the base of the mud, in feet below mean lower low water are shown in figure 1. Figure 2 shows the profile of sediments on a section parallel to the San Francisco-Oakland Bay Bridge.

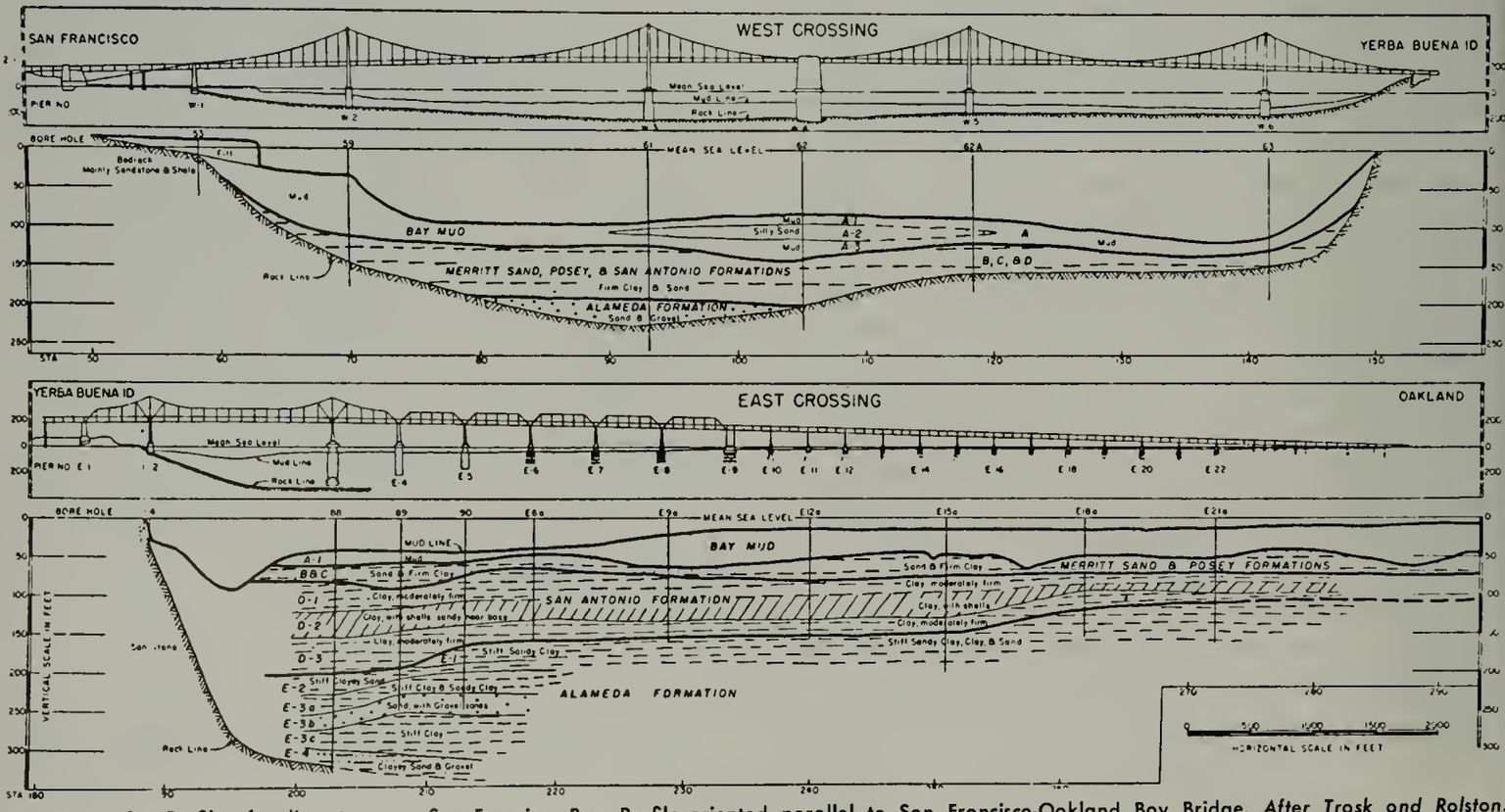
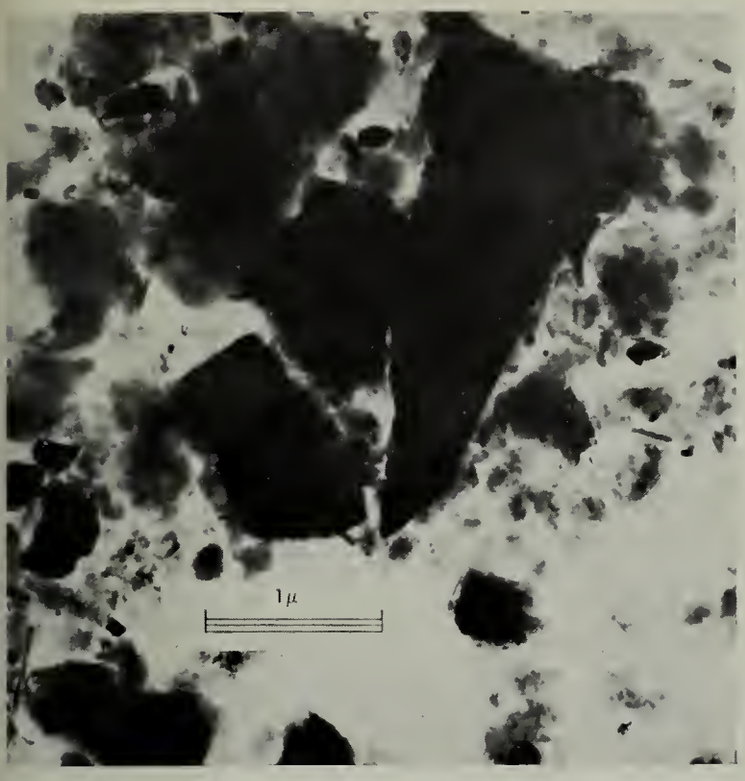


Figure 2. Profile of sediments ocross San Froncisco Bay. Profile oriented porollel to Son Froncisco-Ookland Boy Bridge. *After Trosk ond Rolston.*



Phata 1. Electran phatamicragraph af recently deposited bay mud.

Phata 2. Bearing capacity failure in bay mud resulting fram taa rapid fill placement.

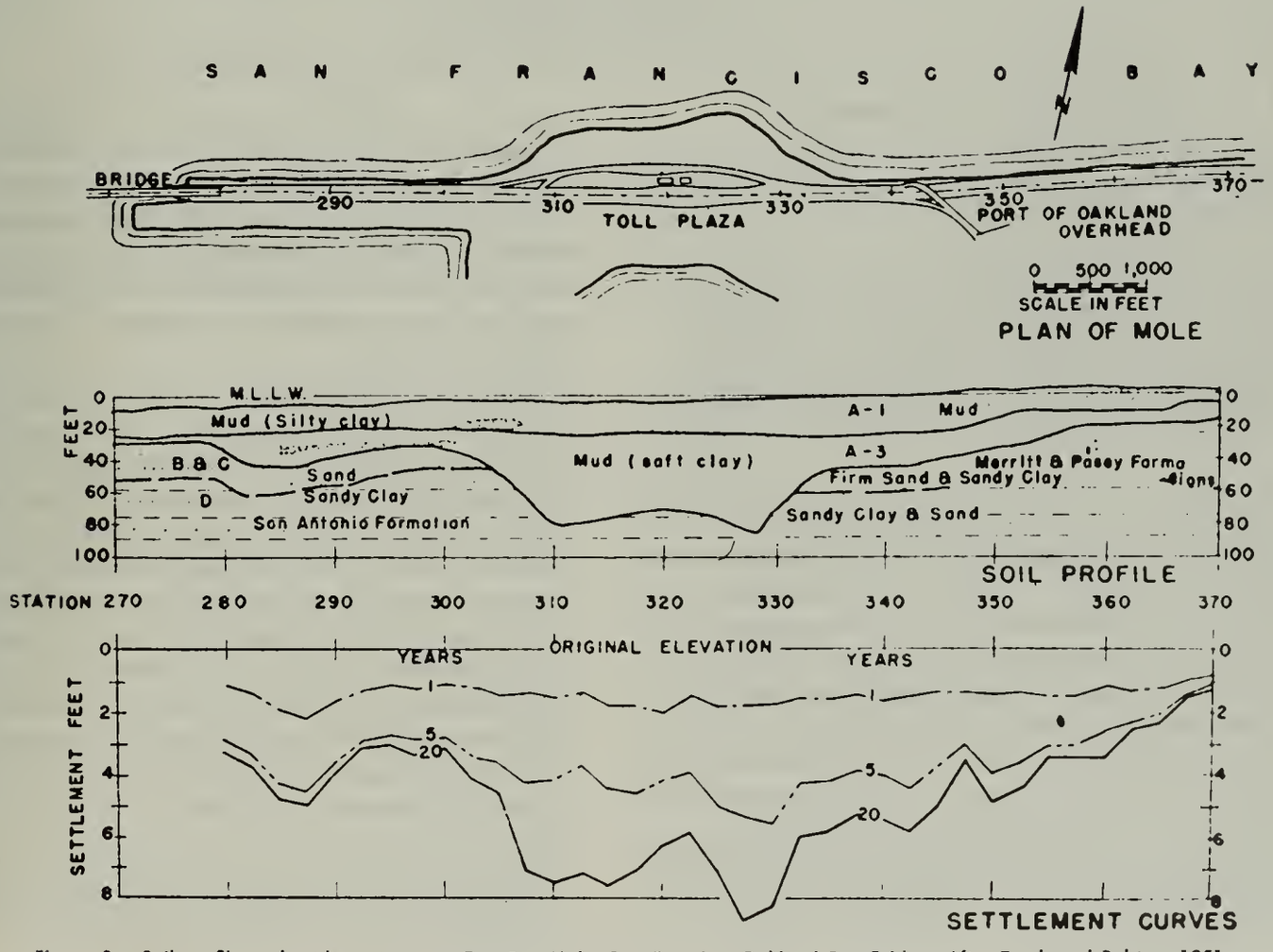


Figure 3. Sail prafile and settlement curves, East Bay Male, San Francisca-Oakland Bay Bridge. *After Trask and Ralstan, 1951.*

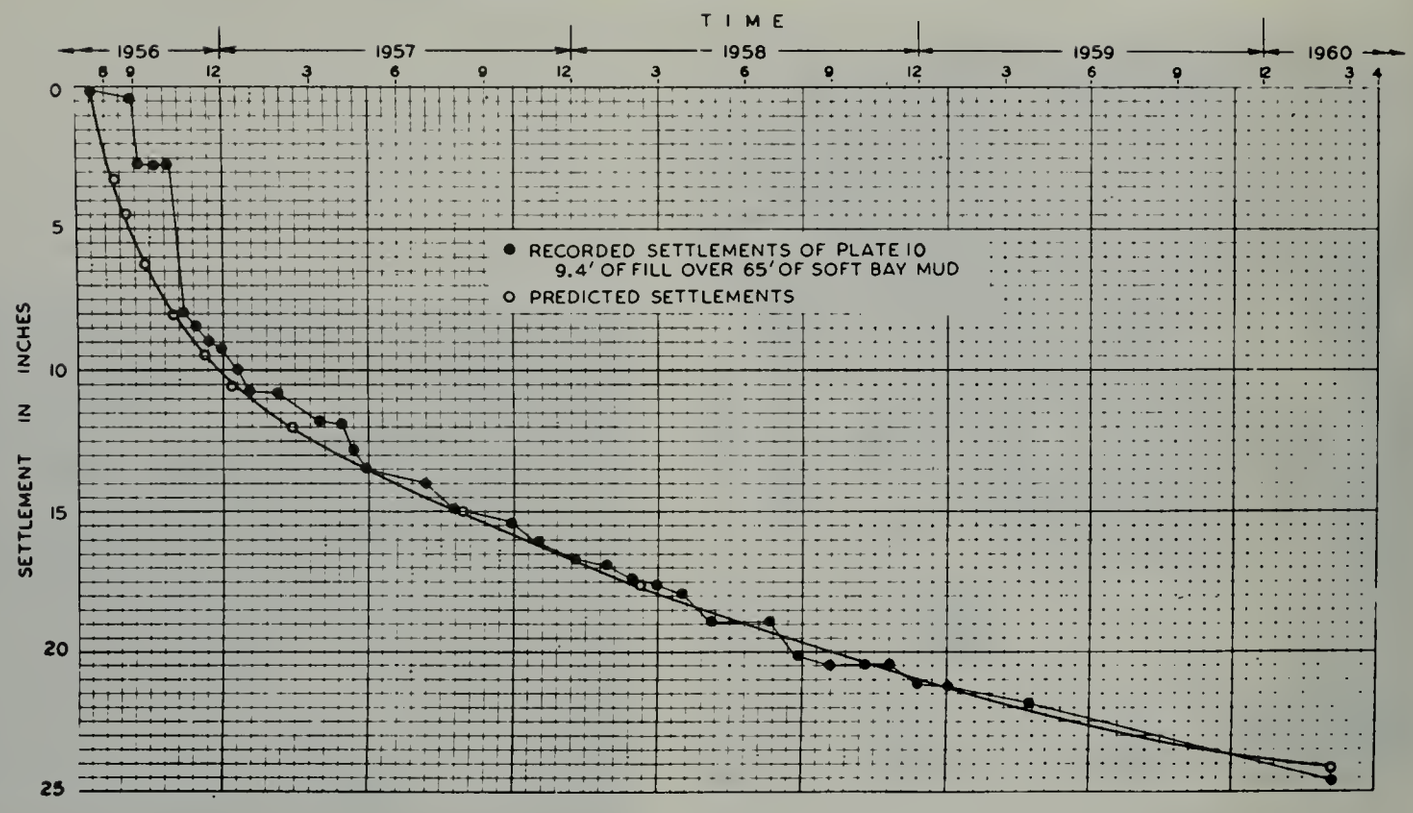


Figure 4. Observed and predicted settlements, South San Francisco Industrial Park. *Courtesy Dames and Moore.*

COMPOSITION AND ENGINEERING PROPERTIES OF BAY MUD

A general soil engineering description of the bay mud might be as follows:*

> A medium to dark gray, soft, silty clay becoming firmer with depth, containing varying amounts of shells and organic matter. In some areas, the upper part of the mud contains interbedded, thin lenses of fine to medium sand. The material is moderately sensitive to remolding; has a low undisturbed strength; is very compressible; and possesses a medium to high plasticity.

Not many detailed compositional analyses of the bay mud appear to have been made. Analysis by the author of recently deposited muds from several points around San Francisco Bay by X-ray diffraction indicates that the material contains a great number and variety of the different clay materials. The analysis showed the presence of montmorillonite, kaolin, vermiculite, and mica and/or hydrous mica. Quartz is also readily detectable. This wide variety of minerals probably reflects the variety of source materials from which the sediment was derived. An electron photomicrograph of a finer than two micron fraction of this sediment is shown in photo 1. The wide variety of particle sizes and shapes is consistent with the presence of several minerals. The tubular or rod-shaped particles visible in this picture suggest that the kaolin mineral may actually be halloysite, as halloysite occurs in particles of this form.

The properties of the bay mud are not uniform throughout San Francisco Bay. The general orders of magnitude of the significant engineering properties and the variability in properties between different points in the Bay may be seen from the data in Table 1. It may be seen that there are significant differences in water content, plasticity and compressibility * for the mud of different areas. It should be noted also that the values listed in Table 1 represent the range of properties over the depth of the mud. In general, the water content decreases with depth and the unit weight and strength increase with depth, as a result of the increase in pressure with depth. In some areas there

* Definitions of the soil mechanics terms used in this paper may be found in the "Glossary of Terms and Definitions in Soil Mechanics," Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, Paper 1826, October 1958.

* The compression index in Table 1 is defined as the slope of the virgin portion of the void ratio—log pressure curve. It is equal to the change in void ratio per logarithmic cycle change in pressure.

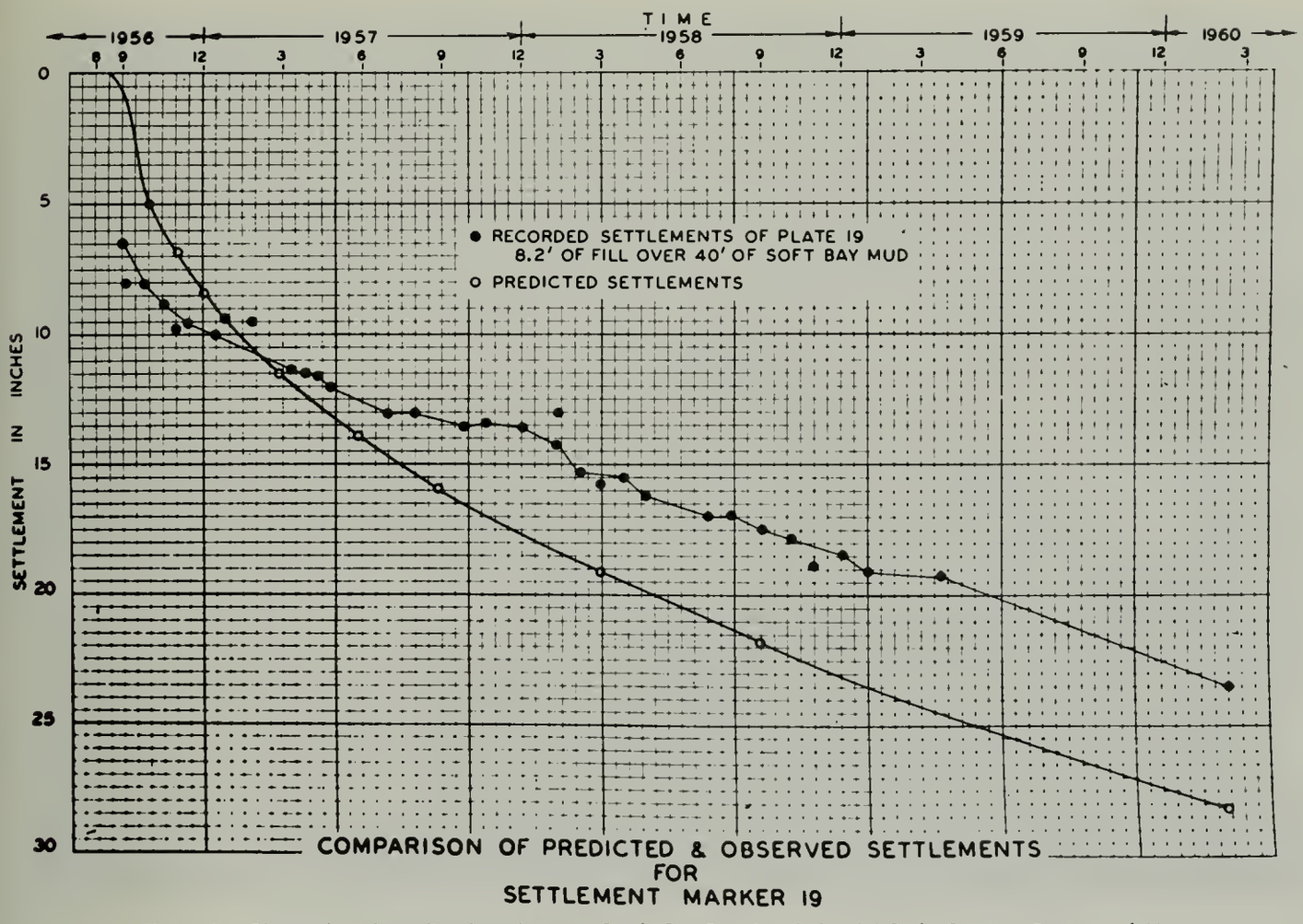


Figure 5. Observed and predicted settlements, South San Francisco Industrial Park. *Courtesy Dames and Moore.*

is a significant increase in the strength and density, and decrease in moisture content above a point about five feet below the upper surface of the mud. The probable explanation for these observations is that the upper few feet of the deposit were exposed at some time during their history and subjected to air drying.

The significant conclusions to be drawn from Table 1 are that the bay mud is, in general, a very weak and compressible material, its natural water content and plasticity are high, and this combination of properties is one that spells foundation problems. In addition, it may be noted that the bay mud has a ratio of undisturbed to remolded strengths, or sensitivity, of from about 2 to 10. Thus the mud has a structure that is rather sensitive to disturbance. The disturbed or remolded material exhibits pronounced thixotropic behavior, almost doubling in strength as a result of aging at constant water content within a week after remolding. A final point of interest in connection with the properties of the bay mud is that the material may be somewhat metastable *in situ*. It was found, for example, that air drying a sample from the deposit underlying Hamilton Air Force Base resulted in a decrease in liquid limit from 91 percent to 71 percent and increase in plastic limit from 29 percent to 35 percent. Such irreversible changes in properties could result from such effects as alteration of the organic matter or cation fixation during the drying process.

ENGINEERING PROBLEMS ASSOCIATED WITH BAY MUD

The majority of engineering problems that arise in connection with the bay mud result from the very low strength and high compressibility of the material. A few of the problems that are frequently encountered may be listed.

1. Failure of the mud due to impased laads or to excavations. Phata 2 presents a phatagraphic record of what can happen if an overlaad is ploced an the mud. A complete bearing copocity failure has accurred leading to a displocement of o large moss of material.
2. Large settlements caused by filling or building canstructian. The magnitude of tatal settlement, maximum differential settlements and rate of settlement all become of great impartance. It is difficult to gain an appreciation of the settlements that ore likely ta result from load opplicatian to the mud an the basis of the campressian index values listed in Table 1. A mare graphic illustration is given by figure 3, which shows the settlement af the male causeway ot the east end af the San Francisca-Oakland Bay Bridge. The pressure increase coused by constructian of the fill amaunted ta abaut ane tan per square foat. It may be seen fram figure 3 that settlements af mare than eight feet taak place during the first 20 years after canstruction. The settlement varies almast directly with the thickness of the underlying mud and at the end af 20 years omaunted to appraximately 10 percent af the thickness af the

Photo 3. Pile pulled from pile cap as a result of down drag of consolidating bay mud.

mud. It is also readily apparent that the variable thickness of mud within any given project area can pose serious differential settlement problems.

3. Support for piles and the consolidation of bay mud around piles. The low shearing strength and the compressibility of the bay mud makes it a poor formation for the support of friction piles. It becomes necessary, therefore, to carry building loads through the mud to the firmer strata below, which may require the use of long piles. In some cases the driving of piles with its remolding effect on the clay or the placement of fill at the surface around a pile foundation can lead to consolidation within the mud stratum. If the piles derive their support through point bearing on an underlying stratum, the consolidation of the soft clay can cause a down drag on the pile sufficient to create an overload on the bearing stratum. A possible result of this is shown in Photo 3 where a pile has been pulled completely down out of its pile cap.

Fortunately, complete failures or serious foundation distress such as shown in these photographs need not accompany all construction operations in or on bay mud. The application of modern techniques of soil mechanics and construction along with an awareness by engineers of the many problems associated with deposits such as the bay mud permit the preparation of safe designs. Large areas of marginal land and mud flats underlain by appreciable thickness of bay mud, for example, have been successfully developed into usable land through the controlled placement of fill. The detailed nature and extent of the various subsoil deposits are first established by means of a thorough program of borings, and the strength and consolidation properties of the foundation materials are established from laboratory tests on undisturbed samples. Calculations may then be made which will furnish information on such factors as the permissible rate of fill placement so that the supporting capacity of the foundation will not be exceeded, the final ground surface elevations for different thicknesses of fill, rates of settlement, and tolerable fill slopes at the edges of the filled area.

Examples of the successful application of these methods are shown in Photos 4 and 5. Photo 4 is a photograph of the recently developed south shore area of Alameda as it appeared soon after the completion of filling operations. The original area was a tidal flat. Sand fill was hydraulically placed over a considerable thickness of soft bay mud. Although large settlements are anticipated, it was possible to establish the initial fill elevations such that the final elevations are predetermined, and to design the structures and other facilities within the area with regard to subsequent settlements. Settlement plates have been placed throughout the area and periodic level readings permit a continuous com-

Photo 4. Successful site development over o thick deposit of mud, Alomedo south shore.

parison between actual and predicted behavior and the adjustment of predictions where necessary.

Photo 5 illustrates a recently completed industrial park in South San Francisco which was reclaimed from a 280 acre section of tideland. Fill was taken from a large hill adjacent to the site and the hill area itself was then developed as an industrial park. Points 10 and 19, Photo 5, indicate the location of two of the settlement markers installed to enable a comparison between predicted and actual behavior. Figure 4 shows the results for Marker 10, and figure 5 for Marker 19. It may be seen that the agreement at Marker 10 is excellent, where 9.4 feet of fill have been placed over 65 feet of mud. The agreement is not quite as good at Marker 19, with the actual settlement being somewhat less than the predicted throughout the period of measurement. At this location, 8.2 feet of fill have been placed over 40 feet of soft bay mud. This result would indicate either that the settlement is taking place at a slower rate than predicted or that the magnitude of the settlement will be somewhat less than originally predicted; however, a knowledge of the form of settlement-time curves derived from theoretical considerations permits appropriate adjustment of the predictions to conform with the present observations.

Soil mechanics principles have been applied successfully to the solution of foundation problems associated with bay mud other than those in connection with settlements as described above. For example, combined analysis of consolidation and shear strength have permitted the construction of embankments on mud deposits at such a rate that the buildup in strength due to consolidation can keep pace with the increased stresses induced by filling operations without danger of foundation failure. Studies of the action of soft clays along friction piles have permitted more rational and economical foundation designs for structures and prevention of behavior such as shown in Photo 3.

Research is continuing on such problems as the development of improved theories and test procedures for use in settlement predictions, the fundamental factors controlling the strength of soft clays, the fabric and physical chemistry of clays, and their relation to engineering behavior, and the behavior of soft clays under dynamic stresses, e.g., earthquake and blast loadings. Continued research in such areas is vital for improved understanding of behavioral mechanisms and continued improvement in the solutions to engineering problems associated with such materials.

Photo 5. Industrial Park, South San Francisco, developed by filling over thick boy mud. *Courtesy Dames and Moore.*

CONCLUSION

Of the several sediments found in the San Francisco Bay area, the soft bay mud poses the most serious engineering problems. The low strength and high compressibility of the muds, coupled with the variable thicknesses of the deposits, resulting from the filling of ancient valleys with muds, are responsible for these problems. The major problems are generally associated with the failure of the mud under imposed loads and excessive total and differential settlements after placement of fills or structures above the mud. Fortunately, developments in soil mechanics now permit the successful solution of the majority of the engineering problems that arise on projects where such materials are encountered.

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FRACTURE TRACES IN THE TUSCAN FORMATION, NORTHERN CALIFORNIA

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ABSTRACT

Photointerpretation was used to recognize and delineate several zones of fracture traces in the Tuscan Formation, north of Chico, California. Field checking established that the fracture traces were the surface expression of small displacement fractures. In the western zone, the fractures dip steeply, and there is little or no separation of the near-horizontal beds through which they pass. This zone affects the flow of groundwater originating from both surface runoff and fossil sedimentary sources. The fractures in this zone are parallel to gentle folds and the fractures are thought to have originated by structural adjustment of the Tuscan Formation during folding.

INTRODUCTION

A zone of fracture traces parallel to the eastern margin of Sacramento Valley (western zone, figure 1), was recognized during the preparation of a reconnaissance geologic map of the Richardson Springs quadrangle (Burnett, 1961). The zone was first noted as nearly parallel fracture traces on aerial photographs, and during photointerpretation of the surrounding region, similar features were recognized to the north and east (eastern zone, figure 1).

The data presented in this report were obtained from the study of aerial photographs and during approximately five days of field work in selected areas. The aerial photographs used include the QE and EJ series of the U.S. Geological Survey and the index photo mosaics of Shasta and Tehama County prepared by the U.S. Department of Agriculture, Production and Marketing Administration.

NOMENCLATURE

The term "fracture trace" as used follows the nomenclature of Lattman (1958) who presented the following definition:

> "A photogeologic fracture trace is a natural linear feature consisting of topographic, vegetation, or soil tonal alignments, visible primarily on aerial photographs, and expressed continuously for less than one mile. Only natural linear features not obviously related to outcrop pattern of tilted beds, lineation and foliation, and stratigraphic contacts are classified as fracture traces. Included in this term are joints mapped on aerial photographs where bare rock is observed."

In this paper, a photogeologic fracture trace is the surface expression of many individual fractures in the rock. Certain areas of many square miles contain hundreds of fracture traces (many more than are found in adjacent areas) and these areas are termed "zones of fracture traces".

A fracture is a small-scale feature which can only be seen on the ground. It is commonly ⅛ to 1/32 inch in width and usually cannot be followed for more than three feet before it merges with another fracture or dies out completely. The term "fracture" does not imply commitment as to direction or amount of displacement.

A fracture trace is an intermediate-scale feature which is made up of many hundreds or thousands of fractures. A fracture trace can best be identified and followed on aerial photographs, but it can also be seen on the ground from a favorable vantage point. It is commonly 10 to 40 feet in width and can be continuously followed on aerial photographs for one-half to one mile.

A zone of fracture traces is a large-scale feature which is made up of many tens or hundreds of fracture traces. A zone of fracture traces can only be seen in its entirety on aerial photographs. It ranges from a fraction of a mile to many miles in width and is many miles in length.

0 1 2 3 4 5 MILES
SCALE
REDDING
RED BLUFF
CHICO
LOCATION MAP
BLACK BUTTE 2667'
INSKIP HILL 3103'
TUSCAN BUTTES 1868'
PAYNES CREEK
RED BLUFF
Tuscan Springs
Battle Creek
South Fork Battle Creek
Antelope Creek
Salt Creek
Sacramento River
Dry Creek
EASTERN ZONE
WESTERN ZONE
40° 15'
36
99W
99E
N
Qpv
Pv
Pv^p
Qal
Qrv^b
Ku

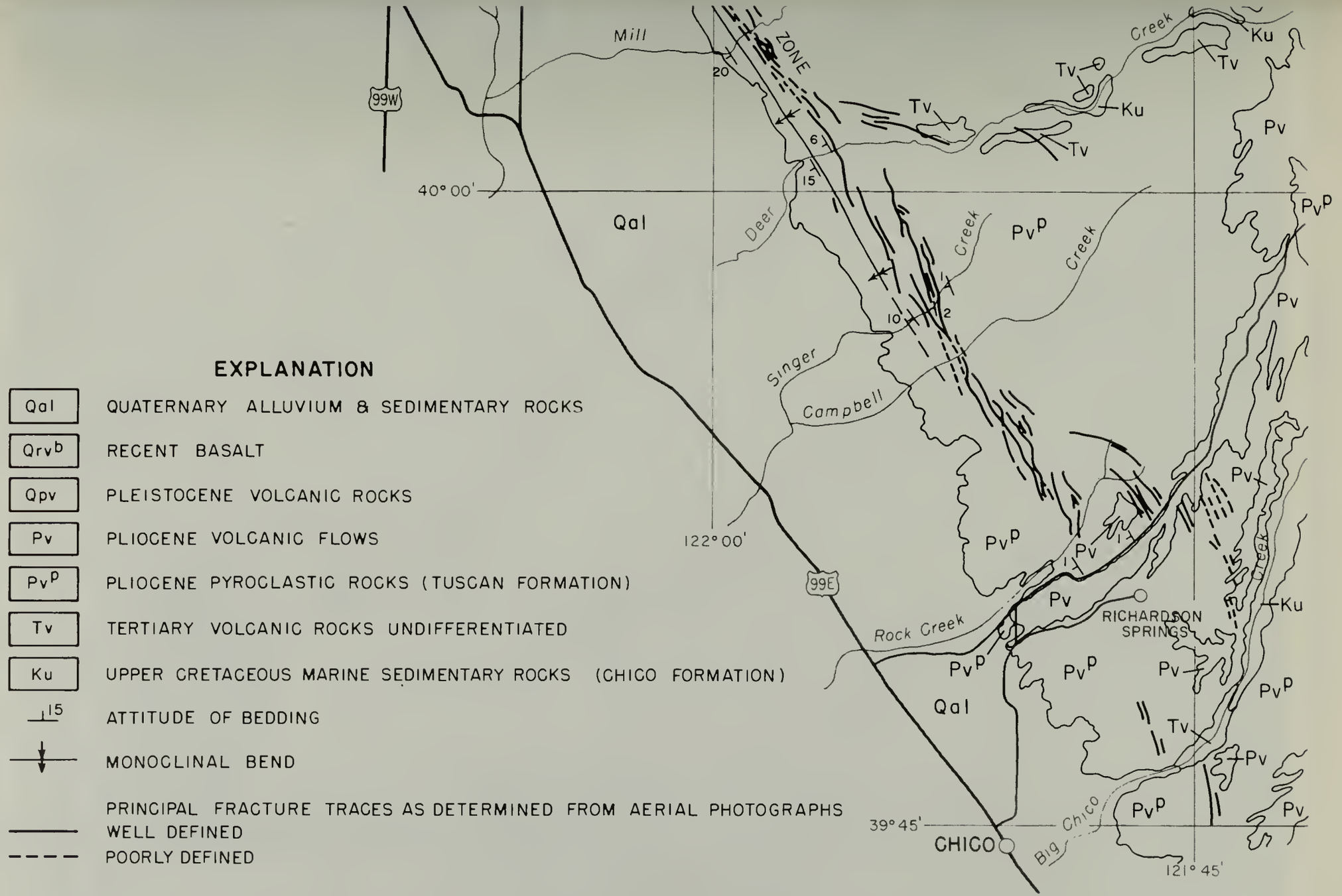
EXPLANATION
Qal QUATERNARY ALLUVIUM & SEDIMENTARY ROCKS
Qrvb RECENT BASALT
Qpv PLEISTOCENE VOLCANIC ROCKS
Pv PLIOCENE VOLCANIC FLOWS
Pvp PLIOCENE PYROCLASTIC ROCKS (TUSCAN FORMATION)
Tv TERTIARY VOLCANIC ROCKS UNDIFFERENTIATED
Ku UPPER CRETACEOUS MARINE SEDIMENTARY ROCKS (CHICO FORMATION)
15 ATTITUDE OF BEDDING
MONOCLINAL BEND
PRINCIPAL FRACTURE TRACES AS DETERMINED FROM AERIAL PHOTOGRAPHS
WELL DEFINED
POORLY DEFINED
99W
99E
ZONE
Mill
Deer
Creek
Singer
Campbell
Rock Creek
Big Chico
RICHARDSON SPRINGS
CHICO
40° 00'
122° 00'
39° 45'
121° 45'

Figure 1.

Photo 1. Western zone of fracture traces at Singer Creek. Note displacement of bedding, as expressed by vegetation, near the center of the top of the photograph. *(U.S. Geological Survey aerial photograph EJ 1-176.)*

DISTRIBUTION

The fracture traces are located in east-central Tehama County and adjoining portions of Butte and Shasta Counties. Most of them are found in two zones which are very different in their configuration. The western zone, which was studied in greater detail, is straight and extends for 30 miles from Richardson Springs northwestward to Tuscan Springs; it averages one to two miles in width throughout most of its length. The eastern zone is a wide, arcuate zone of discontinuous fracture traces that extends from the vicinity of Iron Mountain north of Deer Creek to the town of Paynes Creek on California Highway 36. It is approximately 20 miles in length and ranges in width from 10 miles at Antelope Creek to less than two miles at Iron Mountain. A smaller zone of fracture traces, isolated from these two, has been recognized two miles west of Black Butte on the Old Black Butte Road in Shasta County.

GENERAL DESCRIPTION

Most of the fracture traces are confined to the Tuscan Formation of Pliocene age, although some may be followed on aerial photographs across thin Pliocene volcanic flows that overlie the Tuscan Formation in many areas. The Tuscan Formation consists of basaltic and andesitic volcanic mudflow deposits, and lesser amounts of tuff, tuff-breccia, and interbedded sand, gravel, and volcanic flows.

When observed in the field, the fracture traces proved to be bands of vegetation, including aligned trees, that are much more luxuriant than areas between the traces. On close inspection, individual stalks of grass are occasionally found to be aligned; presumably this alignment is along a buried fracture. The fractures can be seen on the ground in the steeper, well-exposed canyon walls, but they are covered by soil in areas of gentler topography. At close range, the fracture traces are difficult to recognize, because the alignment of vegetation is indistinct unless viewed from a distance. In no case was an older or younger formation found in fault contact with the Tuscan Formation along one of these fracture traces.

The fractures within a fracture trace are channels of groundwater storage and flow that have favored the growth of vegetation, and it is for this reason that the fracture traces can be followed for some distance on aerial photographs. Within the Tuscan Formation, groundwater normally flows along sand and gravel beds above an impermeable member, and the growth of vegetation is also favored where these near-horizontal beds intersect the topographic surface. Both of these kinds of vegetational zones can be identified on photograph 1. The fracture traces are represented by dark lines that cross the topography with little change of direction, whereas the surface exposures of the permeable beds are indicated by the sinuous lines that approximately coincide with the topographic contours.

DETAILED FEATURES OF THE WESTERN ZONE

The western zone is straight, although fracture traces within the zone commonly display curved, braided, or en echelon patterns. Most fracture traces have a near-vertical dip, but this may range from 60° NE to 60° SW; the variation in degree and direction of dip has no consistent pattern. Separation of the beds on either side of a fracture trace has been observed at several points but this, too, is not consistent, either in magnitude or sense of displacement. Sixty feet of vertical separation of the bedding, with the west side down, was noted at Singer Creek (photograph 1), and 15 feet of vertical separation, with the west side up, was observed at Deer Creek. At Rock Creek, Dye Creek, and Antelope Creek the fractures within a fracture trace pass through well-exposed bedding planes within the Tuscan Formation without any displacement on a large scale. There is no evidence for extensive lateral displacement along these traces. The observed displacements and the restriction of all fracture traces to a well-defined linear zone is considered to be evidence that the fractures within the fracture traces are faults, although the displacement along most of the fractures is very small.

The rock within a fracture trace is not well exposed due to the more intense effects of weathering along the fractures. The fracture trace usually is covered with soil and frequently is marked by marshy spring seepages. Well exposed outcrops within a fracture trace are cut by many tight fractures that are parallel to one another and spaced three to twelve inches apart. Fault gouge usually is not developed and, where present, is no more than one or two inches wide. * The fractures cut through the ashy matrix of the Tuscan Formation and avoid lithic clasts wherever these are present. Separation of several inches or less can be observed in the few places where suitable exposures are found; each fracture seems to have accounted for no more true displacement than this amount.

Several well-defined fracture traces of the western zone pass through the spring area at Tuscan Springs where Anderson (1933) described a series of open anticlines and synclines with limbs dipping 10° to 20°. The axes of these folds are parallel to the northwesterly trend of the fracture traces. Richardson Springs lies directly on strike with the western zone but is two

* W. R. Hail, Engineering Geologist, California Department of Water Resources. Oral communication, 1961.

Photo 2. View north along the northeastern border of the Sacramento Valley. The western zone of fracture traces is defined by aligned trees in the middleground. The canyon wall of Mill Creek, in the foreground, exposes a monoclinal bend which may have caused the fracturing in this area. Tuscan Buttes in the right background. *Photo courtesy California Department of Water Resources.*

miles south of the nearest fracture traces that could be detected on the aerial photographs.

The water from both of these spring areas is a cool, dilute, saline solution with a high sulfur content. Natural gas seeps are present in the vicinity of both spring areas (Waring, 1915; O'Brien, 1949). Sassolite, the natural mineral equivalent of boric acid, has been reported at Tuscan Springs (Murdoch and Webb, 1956). White (1957) concludes that Tuscan Springs contains water of connate or metamorphic origin; that is, the water is derived from the compaction and metamorphism of sedimentary rocks rather than from a primary magmatic source.

Natural gas seeps also are reported (Rogers, 1962) at an exposure of Cretaceous rocks along Salt Creek, two miles south of Tuscan Springs. This locality is one-half mile north of, and on strike with, fracture traces of the western zone.

Anderson (1933, p. 240) describes a westward dipping monocline at the westernmost exposure of the Tuscan Formation:

> "North from Chico to Red Bluff, the western border of the Tuscan is marked by a sharp monoclinal fold which accounts for the rather straight line along the southwestern border of the exposed area of the Tuscan."

The upper bend of this monocline is the only exposed portion, being indicated by a steepening of the dip from 1° or 2° SW to approximately 20° SW. The lower bend is known from well data. Along most of its 30 mile length, the western zone of fracture traces is parallel to the upper bend of the monocline, and is narrowly confined along the eastern margin of this bend. To the north, the monocline merges with gentle folds in the vicinity of Tuscan Springs; to the south, the monoclinal bend gradually flattens into a homocline slightly north of the road to Richardson Springs. At both ends of the monocline, the fracture traces spread out over a wide area and abandon their usual confinement to a narrow zone.

ORIGIN OF THE WESTERN ZONE

The western zone of fracturing bears a close areal relationship to folding within the Tuscan Formation, and all but a very few of the fracture traces that have been recognized are restricted to this formation. The detailed features of the western zone indicate that these fractures traces are the surface expression of faults, although the displacement on nearly every fault is quite small, and no consistent pattern can be seen in the relative displacement of adjacent blocks. No evidence was found for appreciable displacement of the unfractured blocks on either side of the western zone of fracturing. These factors combine to suggest that the western zone was produced by structural adjustment of the Tuscan Formation during the folding which produced the monocline and the anticlines and synclines at Tuscan Springs.

The mineral water associated with the fracture traces is not considered to be evidence that the fractures extend to great depth. White (1957) suggests that the water at Tuscan Springs is derived from sedimentary rocks, and the association of natural gas with the mineral water supports this conclusion. Sedimentary rocks of the Cretaceous Chico Formation underlie the Tuscan Formation at both of the spring areas. The mineral waters may reach the surface through these fractures at Richardson Springs, and through a window in the Tuscan Formation exposing Cretaceous rocks at Tuscan Springs. No evidence was found that the fracturing extends below the base of the Tuscan Formation and this would not be expected if, as proposed above, the fracturing is caused by breaking of the Tuscan Formation during folding. The monocline could have been caused by vertical movement along a deep-seated fault which was active after the Tuscan Formation was laid down. If such a fault does exist, it would have only a second order bearing on the origin of the fractures, in that it produced the monocline which, in turn, produced the fractures.

THE EASTERN ZONE AND OTHER AREAS OF FRACTURING

The fracture traces of the eastern zone (figure 1) can readily be seen on aerial photographs or from vantage points, such as the fire lookout on Inskip Hill, but they were not studied in the field during the preparation of this paper.

Most of the fracture traces of the eastern zone are interrupted by stream canyons, such as Antelope Creek and Mill Creek. These discontinuities apparently are due to poor conditions for the growth of vegetation on the steep canyon walls rather than to an actual termination of the presumed fractures. By the same reasoning, other areas of fracturing may not have been recognized because vegetation is not well developed along them.

The zone of fracture traces in the exposure of the Tuscan Formation west of Black Butte is on strike with the northward extension of the eastern zone, and the two zones are probably connected by unexposed fractures. The area between these two zones is covered by thick basalt flows which would have obliterated any evidence of the fracturing. The fracture traces are not found on thick accumulations of these later flows, either because they were laid down after the fracturing took place or because they behaved differently than

the Tuscan Formation during deformation and fracturing did not develop.

Although the structure of the Tuscan Formation in the vicinity of the eastern zone is not well known, it seems probable that this zone was produced in a manner similar to the western zone. The broad distribution and arcuate trend of these fracture traces suggest that they reflect the presence of gentle anticlinal and synclinal folds.

CONCLUSIONS

The fracture traces were found to be the surface expression of swarms of near vertical fractures, each of which has a very small displacement. These fractures are parallel to gentle folds, both monoclinal and anticlinal-synclinal, and the fractures are thought to have originated by structural adjustment of the Tuscan Formation during this folding. The fracture traces are conspicuous on aerial photographs because the fractures have diverted the normal flow of groundwater which has increased the growth of vegetation along their surface extent. The fractures are related to mineral springs and natural gas seeps and may have provided these fluids with access channels to the surface. The fracture traces are significant, beyond their relationship to the flow of groundwater, because they reflect the presence of known folding in the western zone and may predict the presence of as yet unrecognized folding in the eastern zone.

ACKNOWLEDGMENT

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FOSSIL EVIDENCE FOR MAXIMUM AGE OF METAMORPHISM IN PART OF THE FRANCISCAN FORMATION, NORTHERN COAST RANGES, CALIFORNIA

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ABSTRACT

A fossil identified as *Buchia crassicollis* (Keyserling) was found near Anthony Peak in weakly metamorphosed rocks of the Franciscan Formation. The Early Cretaceous (Valanginian) age of this fossil establishes a maximum age for the metaporphism in this area.

A pelecypod of early Early Cretaceous age has recently (1963) been found in weakly metamorphosed rocks of the Franciscan Formation in the northern Coast Ranges of California. To this writer's knowledge this is the first identifiable fossil from Franciscan rocks which have been subjected to glaucophane schist facies metamorphism.

The fossil was found by Lee Ruhn, a summer employee with the U. S. Forest Service, near Wells Cabin Camp (NE¼ Sec. 22, T. 23N., R. 10W.) in the Anthony Peak quadrangle about one mile southeast of Anthony Peak (Figure 1). The fossil locality is at the base of a large prominent knob of conglomerate near the crest of the ridge. It lies a few hundred yards south of the intersection between the county road and Wells Cabin Camp turnoff and a few yards west of the ridge crest trail. The writer visited the outcrop but was unable to find any additional fossils. The fossil is from sheared graywacke associated with conglomerate and slate. Dr. J. W. Durham of the Department of Paleontology, University of California, Berkeley, identified the fossil as *Buchia crassicollis* (Keyserling) of early Early Cretaceous (Valanginian) age. The specimen is filed in the Paleontology Museum, University of California, Berkeley, and has been assigned U.C.M.P. Hypotype No. 15038. Taliaferro (1943, p. 190) reported that the rocks on the Paskenta road east of Anthony Peak contain *Aucella*, now known as *Buchia*, "similar to those in the Franciscan and Knoxville." The locality described in this report is probably near one of Taliaferro's localities.

The rocks in this part of the northern Coast Ranges have been subjected to regional glaucophane schist facies metamorphism (Ghent, 1963). Weakly metamorphosed clastic sedimentary rocks in the vicinity of Wells Cabin Camp and Anthony Peak contain lawsonite and metamorphic aragonite, which are diagnostic minerals of the glaucophane schist facies. Fine-grained matrix material clinging to the specimen of *Buchia* also contains small tabular crystals of lawsonite. These data indicate a maximum age of early Early Cretaceous (Valanginian) for the metamorphism in this part of the Franciscan Formation.

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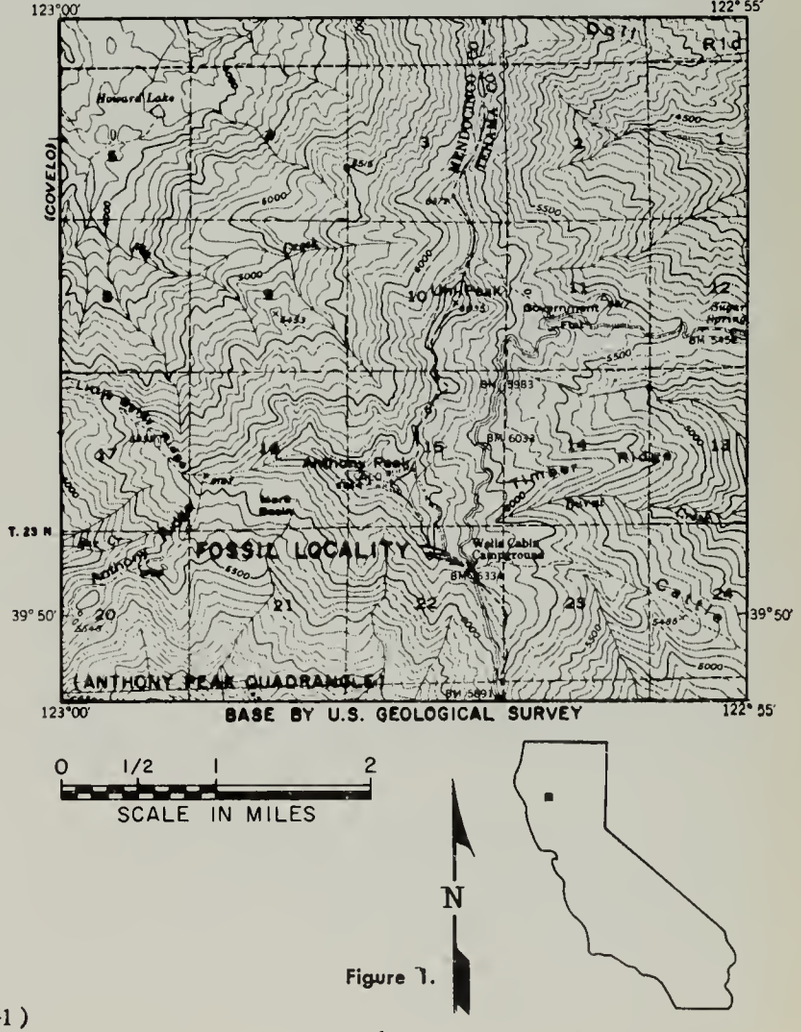

Figure 1.

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